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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

SOFTWARE DEFINED RADIO DESIGN FOR SYNCHRONIZATION OF 802.11A RECEIVER

by

Juan Luis Sanfuentes

September 2007

Thesis Advisor:	Frank Kragh
Second Reader:	Roberto Cristi

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      Constant improvements in techniques applied to different radio communication system stages, including coding, modulation, synchronization and security, make any implementation quickly obsolete. On the other hand, different communication standards used among military and public safety agencies make difficult the necessary interoperability. These reasons force users to replace equipment frequently, increasing cost and implementation time. Software Defined Radios (SDRs), partly implemented in software, can solve these problems, making full use of programmable modules. This thesis presents an implementation of the necessary algorithms that solve the synchronization requirements of IEEE 802.11a WLAN receivers. This is a continuation of a previous thesis effort, where the post-synchronization steps of the receiver were addressed. The software utilized for this purpose is the Open Source SCA Implementation::Embedded (OSSIE), developed by Virginia Tech. Each algorithm was created as a different component, allowing reuse and modularity for the development of future waveforms.

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**SOFTWARE DEFINED RADIO DESIGN
FOR SYNCHRONIZATION OF 802.11A RECEIVER**

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

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ABSTRACT

Constant improvements in techniques applied to different radio communication system stages, including coding, modulation, synchronization and security, make any implementation quickly obsolete. On the other hand, different communication standards used among military and public safety agencies make difficult the necessary interoperability. These reasons force users to replace equipment frequently, increasing cost and implementation time. Software Defined Radios (SDRs), partly implemented in software, can solve these problems, making full use of programmable modules. This thesis presents an implementation of the necessary algorithms that solve the synchronization requirements of IEEE 802.11a WLAN receivers. This is a continuation of a previous thesis effort, where the post-synchronization steps of the receiver were addressed. The software utilized for this purpose is the Open Source SCA Implementation: Embedded (OSSIE), developed by Virginia Tech. Each algorithm was created as a different component, allowing reuse and modularity for the development of future waveforms.

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LIST OF SYMBOLS, ACRONYMS AND ABBREVIATIONS

ADC   Analog to Digital Converter
AWGN   Additive White Gaussian Noise
CP   Cyclic Prefix
DSW   Double Sliding Window
FFT   Fast Fourier Transform
FPGA   Field Programmable Gate Array
ICI   Intercarrier Interference
IF   Intermediate Frequency
IFFT   Inverse Fast Fourier Transform
ISI   Intersymbol Interference
JPEO   Joint Program Executive Office
JTRS   Joint Tactical Radio System
LP   Long Preamble
MAC   Medium Access Control
MMI   Man Machine Interface
OFDM   Orthogonal Frequency Division Multiplexing
OSSIE   Open Source SCA Implementation::Embedded
OWD   OSSIE Waveform Developer
PHY   Physical Layer
PLCP   PHY Layer Convergence Procedure
PPDU   PLCP Protocol Data Unit
PSDU   PHY Layer Service Data Unit
PSK   Phase Shift Keying
QAM   Quadrature Amplitude Modulation
SBR   Software Based Radio
SCA   Software Communication
SDR   Software Defined Radio
SP   Short Preamble
TS   Training Sequence
USB   Universal Serial Bus
WLAN   Wireless Local Area Networks
WNW   Wideband Network Waveform

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EXECUTIVE SUMMARY

This thesis presents a Software Defined Radio (SDR) application for a particular communication system, the synchronization stage of an Orthogonal Frequency Division Multiplexing (OFDM) packet based receiver. The standard chosen for this work is the IEEE 802.11a standard, which specifies Wireless Local Area Network (WLAN) operation in the 5 GHz band. A SDR solution refers to the capacity to reprogram the hardware involved in a communication system, in order to manage different waveforms. The main advantage is the ability to modify the system's characteristics, including modulation, error control coding, carrier frequency and data link protocol, while avoiding the necessity of changing the hardware. This is essential in the military, since disparate equipment, with its particular characteristics and lack of modularity, makes interoperability between branches and allied countries difficult. This new concept has been of great interest in the U.S. Government, where the Joint Tactical Radio System (JTRS), a major program conducted by the Joint Program Executive Office (JPEO), has developed an open source framework denominated the Software Communication Architecture (SCA), which defines the way to configure hardware and software that form a SDR system.

The software utilized for developing the application is the Open Source SCA Implementation::Embedded (OSSIE), a SDR design environment created by Mobile and Portable Radio Research Group (MPRG) based at Virginia Tech University. This software facilitates the design of software components that perform a particular communication task, and the design of waveforms based on the interconnection and configuration of these components.

The synchronization stage of 802.11a extends the functionality of an already developed thesis, which covered the post synchronization stage: signal demodulation and decoding. That work assumed an ideal channel and perfect synchronization and was developed in an earlier version of OSSIE. OFDM has become an attractive alternative for new communication standards due largely to its efficient use of the spectrum, achieving considerable bandwidth efficiency, thereby allowing wireless transmission at high data

rates in a modest bandwidth. A foundational concept behind OFDM is the use of orthogonal sub-carriers that split the transmitted data into different channels, after performing an Inverse Fast Fourier Transform (IFFT), allowing parallel transmission with no self-interference. The use of a Cyclic Prefix (CP) before each OFDM symbol, which consists of the repetition of the symbol tail, allows robustness against multipath due to IFFT properties. Synchronization is crucial with OFDM for successfully receiving the transmitted signal, since the orthogonality can be lost because of incorrect packet detection, symbol synchronization, or a frequency offset.

The synchronization process performed in this application includes coarse and fine packet start detection, coarse and fine frequency detection and correction, channel estimation and compensation, and finally symbol phase tracking and correction. The use of Matlab, a programming language oriented towards engineering calculations, at the beginning of the work was essential for verifying the correct implementation of the algorithms obtained from the literature. After this process, the next step was programming the components in OSSIE and testing them against the results obtained in Matlab. The testing was achieved by creating a waveform that includes the developed components, which processed simulated OFDM signals generated in Matlab. These simulated signals were affected by noise, frequency offset and a multipath channel. The results demonstrated the correct functionality of the components by verifying the digital samples after each component through the use of constellation diagrams.

Future work in this specific implementation includes the development of a component in charge of controlling the necessary hardware to obtain the digital samples that should be passed to the first component in the synchronization stage: the packet detection. Also, work is needed in revising the demodulation and decoding stage components in order to make them compatible with the current version of OSSIE and integrate them with the synchronization components developed in this thesis, obtaining a complete 802.11a receiver working in OSSIE. Finally, work is needed to integrate the software solution onto a suitable hardware platform, in particular one capable of processing the high data rate OFDM signal in real time.

ACKNOWLEDGMENTS

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I. INTRODUCTION

A. OBJECTIVES

The purpose of this thesis is to demonstrate that different components of a radio communication system can be made reconfigurable using software. In particular this work has the following objectives:

- Understand the concepts of SDR and learn how to use OSSIE as a platform to create communication components, and design a desired waveform.
- Learn the synchronization techniques useful for OFDM signals.
- Apply these synchronization algorithms, using the development tool included in OSSIE.
- Prove the functionality of each component, by testing the corresponding waveform by receiving OFDM packets affected by the channel.

B. CONTRIBUTIONS

The present thesis contributes to several organizations, where the use of SDR is becoming important. OFDM synchronization is not only used in 802.11a, but also in others standards including:

- IEEE 802.11g Wireless Local Area Network in the 2.4 GHz band [1],
- IEEE 802.16 Wireless Metropolitan Area Network,
- European Telecommunications Standards Institute (ETSI) Technical Report (TR) 101 496 Digital Audio Broadcasting (DAB),
- ETSI European Standard (EN) 301 701 Digital Video Broadcasting (DVB), and
- International Telecommunications Union (ITU) G-992 Asymmetric Digital Subscriber Line (ADSL).

OFDM is currently used also in the military. An example of this is the Wideband Network Waveform (WNW) [2]. Due to the current success OFDM is undergoing, it seems very likely that future standards will implement it as its principal modulation scheme.

The immediate contribution of this thesis is to increase the library of components under development for the OSSIE community, where Virginia Tech and NPS are collaborating.

The U.S. government is publishing standards, including Software Communication Architecture (SCA) [3], to guide the industry in the development of software defined radio communication systems. The open source feature of OSSIE, allows the industry to use components already developed.

Due to several naval exercises that American and allied navies execute every year, there is a permanent requirement of interoperability, which is achieved by following common tactical procedures and using compatible communication systems. The use of SDR is a valuable alternative to perform the necessary configurations to achieve the required compatibility, avoiding changes in hardware. This thesis contributes to allied navies that have not considered or have just started using SDR in their communication systems, giving them the basic knowledge in this area, and providing them with some components that will permit future developments.

C.   RELATED WORKS

1.   OSSIE

Since OSSIE has been available as a tool that allows development of SDR systems, several works have been executed. The major efforts come from the group that created and continuously upgraded the software: Mobile and Portable Radio Research Group (MPRG) from Virginia Tech [4].

Motivated by research and educational needs, and considering the next generation in communication systems that U.S. Government Institutions will operate, NPS currently is offering a SDR course, which is supported by a dedicated laboratory. As a consequence, some theses have been developed in this area, where OSSIE is the adopted software platform. SDR designs have been produced at NPS for:

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- IS 95B – The Code Division Multiple Access (CDMA)-based 2G cellular phone standard in North America [5].

- IEEE 802.16- A standard for wireless Metropolitan Area Networks [6].

- IEEE 802.11a- An amendment to a wireless Local Area Network standard [7].

The 802.11a thesis work by Leong [7] was developed using OSSIE version 0.5.0, where the different stages needed in both the transmitter and receiver were considered. The receiver uses a total of 18 components for demodulation and decoding, assuming an ideal channel. Simulations were completed, where the obtained results demonstrated the correct functionality of the corresponding components.

The natural next step related to 802.11a receivers is the development of the synchronization stage and channel correction, the subject of the present thesis.

2. OFDM Synchronization

A recent work in OFDM synchronization at NPS is the thesis by Sardana [8], where packet and frequency detection methods were evaluated. Some recommendations in this work emphasize the use of data aided based algorithms. In the case of frequency synchronization, it is shown that the two-step estimation, first coarse and then fine detection, is effective. This is accomplished using both short and long training sequences, as will be described later.

D. THESIS ORGANIZATION

The remaining chapters are organized as follows:

- Chapter II explains all the concepts related to OFDM synchronization and SDR in order to understand the basis of the current work.

- Chapter III explains the design of the algorithms for synchronization, and the simulation results. The main goal of this chapter is to verify the correct functionality of the algorithms.

- Chapter IV examines the application developed in OSSIE, where the development of each particular component is explained.

- Chapter V provides the test results using different 802.11a signals, previously generated in Matlab.

- Chapter VII gives conclusions and discusses recommendations for future work in this particular waveform.

II.   BACKGROUND

A.   SOFTWARE BASED RADIO (SBR)

The concept behind SBR is the capacity to reprogram the hardware involved in a communication system, in order to manage different communication waveforms, as required. The main advantage is the ability to modify the system's characteristics, including modulation, error control coding, carrier frequency and data link protocol, while avoiding the necessity of exchanging the hardware.

The term SBR is used in a generic way to describe this emerging technology, where the terms Software Defined Radio (SDR) and Software Radio (SR) are used depending on the specific stage, within a communication system, where this technology is applied. [9]

1.   Software Defined Radio (SDR)

As introduced in the last paragraph, the terms SDR and SR are part of this software based technology. SDR refers to certain communication tasks that are developed in software; including, in the receiver case, the processing performed after the down conversion process. Software Radio (SR), on the other hand, implies an almost totally software-based solution, where the digitization step occurs as close to the antenna as possible, and all the following steps are developed and managed using software. [9]

SDR is a relatively new area that has been growing, and should be seen as part of the fast development of wireless communications. New technology has helped this quick technical evolution including, among others, the processor's speed. The flexibility of software based implementations makes this alternative an excellent choice to ameliorate the issues that have been raised, including compatibility with recent technology and the desirability of hardware reuse.

Several advantages can be considered, with respect to SDR solutions, including:
- Reuse of hardware,
- Lower implementation cost,
- Compatibility with old equipment,
- Fast adaptability in order to reach interoperability, and
- Easy upgrades in modulation, error control coding, and data link protocols.

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2.   Software Communication Architecture

The Software Communication Architecture (SCA) is an open source framework that defines the way to configure the hardware and software that form a SDR system [10]. A framework is a set of classes that work together for a specific type of software. Using support programs like libraries, it is designed to facilitate software development.

The SCA is mandated by the Joint Tactical Radio System (JTRS), a major program conducted by the Joint Program Executive Office (JPEO) JTRS, which develops solutions intended to satisfy DoD communication interoperability requirements.

Flexibility and platform independence are the main characteristics of the SCA, which allows modularity and facilitates application development. On the other hand, the idea of developing applications independent of the hardware, where at least one General Purpose Processor (GPP) is available, come at the cost of some inefficiencies, including memory allocation problems and latency. [11]

3.   Open Source SCA Implementation: Embedded (OSSIE)

OSSIE is open-source SDR development software. It is a current project developed by Mobile and Portable Radio Research Group (MPRG) based at Virginia Tech University. Created as a solution to implement communication waveforms, it allows SDR application development that follows the SCA specifications. The project is written in the computer languages C++ and python and it has been under continuous development, since 2003 [12]. The goals of OSSIE are based in investigation and educational purposes, from the study of interoperability issues to the training of students in the concepts and development of SDR.

An important tool of OSSIE is the OSSIE Waveform Developer (OWD), which is supporting software that enables rapid design of components and waveforms. Components are applications that execute a specific task in a communication system chain. Selecting the necessary components, the OWD allows the development of a specific type of waveform.

B.   OFDM SYNCHRONIZATION

OFDM signals are used both in broadcast as well as in packet switched transmissions, with different synchronization requirements. In the broadcast case, the receiver has a relatively long period of time for synchronization, whereas in packet systems, time is limited and a fast synchronization is required before and during each packet [13]. Due to differences in this time constraint, the applied algorithms are not the same.

Wireless Local Area Networks (WLANs) are packet switched systems; thus, the following explanation refers to algorithms used in these types of networks.

1.   OFDM Fundamentals

OFDM signals allow splitting a high data rate stream into a parallel number of slow data rate streams, which are transmitted through orthogonal carrier frequencies. The effect of the slow data rate due to the increase in symbol duration is the reduction of the fraction of the symbol duration affected by signal dispersion in time caused by multipath delay spread. At the same time, the bandwidth of each sub-carrier is smaller compared to the channel bandwidth, thus the usual frequency selective fading on the entire 802.11a band is realized as flat fading of each sub-carrier, which is much easier to equalize [14].

Several difficulties arise when utilizing digital multicarrier modulation techniques, including intersymbol interference (ISI) and intercarrier interference (ICI). The former is almost eliminated by using a guard time before every OFDM symbol. The latter is avoided applying a cyclic prefix of the symbol in the guard time, keeping the orthogonality between sub-carriers. [13]

The way to generate an OFDM symbol involves a coding process that ends with a digital modulation mapping, using either Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) on each sub-carrier. Then an Inverse Fast Fourier Transform (IFFT) over a defined number of values is performed, which has the effect of modulating each sub-carrier's symbol by the appropriate complex exponential to create a

complex envelope signal where the symbols are orthogonally frequency division multiplexed with minimally spaced frequencies, for maximum spectral efficiency.
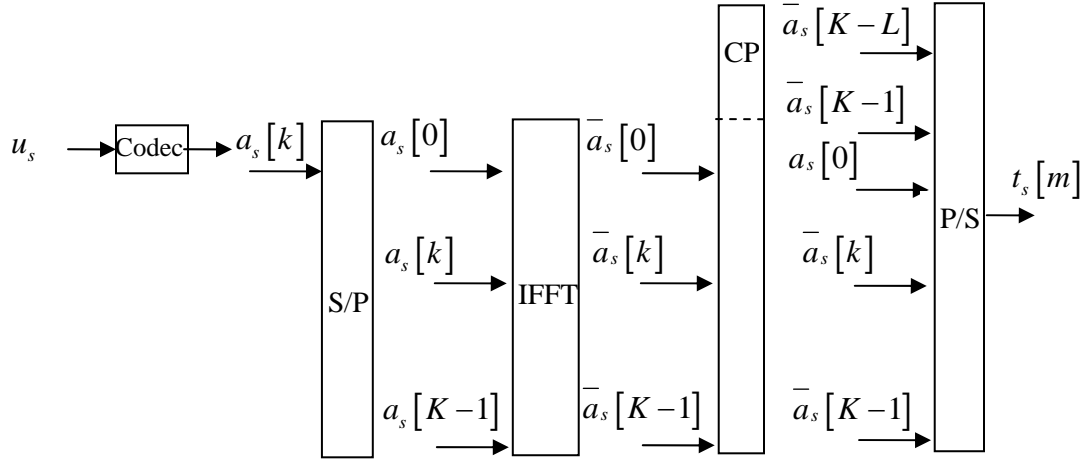
Figure 1.   OFDM symbol generation. (After Ref. [14]).

Figure 1 shows how the sth OFDM symbol is generated, from the sequence $a_s[k]$, $k = 0,...,K-1$, after the coding and modulation process. The length K is the same as the IFFT window. After the IFFT, the OFDM symbol is prepended with a cyclic prefix (CP) of length L time samples to form a discrete time signal of $M = K + L$ time samples. These L CP values are obtained from the end of the IFFT result, which are prepended at the beginning of the symbol, as depicted in Figure 2. The purpose of the time guard is to avoid ISI, and its duration must be greater than the multipath delay spread.
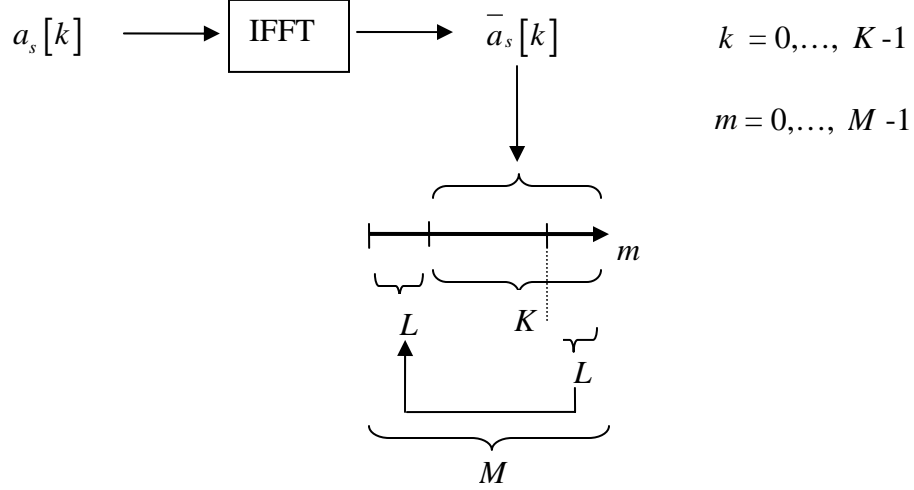
Figure 2.   CP generation (After Ref. [14]).

Finally the transmitted OFDM symbol $t_s[m]$, from Figure 1, can be defined by [14]

$$t_s[m] = \frac{1}{K} \sum_{k=0}^{K-1} a_s[k] e^{j\frac{2\pi}{K}k(m-L)} \tag{1}$$

where $k = 0,...., K-1$, and $m = 0,...., M-1$.

Notice in Equation (1) that each sub-carrier has an integer number of cycles, which is an integer multiple of the inverse of the symbol duration, K [13] [15] This is important to keep the desired orthogonality to avoid ICI [15] [16]. The CP length L should be greater than the average length of the channel impulse response, which is measured as the multipath delay spread.

The receiver counterpart performs similar operations in reverse order to retrieve the transmitted data, where a Fast Fourier Transform (FFT) computation is included. Now, in the receiver case, it is appropriate to explain the reason for the CP. Figure 3 shows a sub-carrier and a delayed version of it, where the CP is not included in the time guard. The absence of signal in the delayed version is going to destroy the perfect tone required inside the FFT window, producing a loss of orthogonality, and thereby inducing

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ICI. Figure 4, on the other hand, depicts the same situation, but now filling the time guard with the CP, keeping a delayed but continuous tone inside the FFT window. [13]
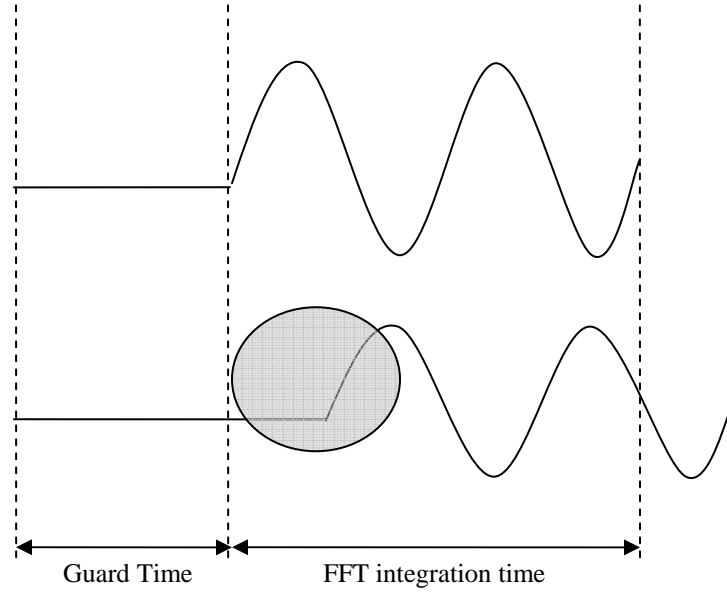
Figure 3.   Delayed sub-carrier without CP (After Ref. [13]).
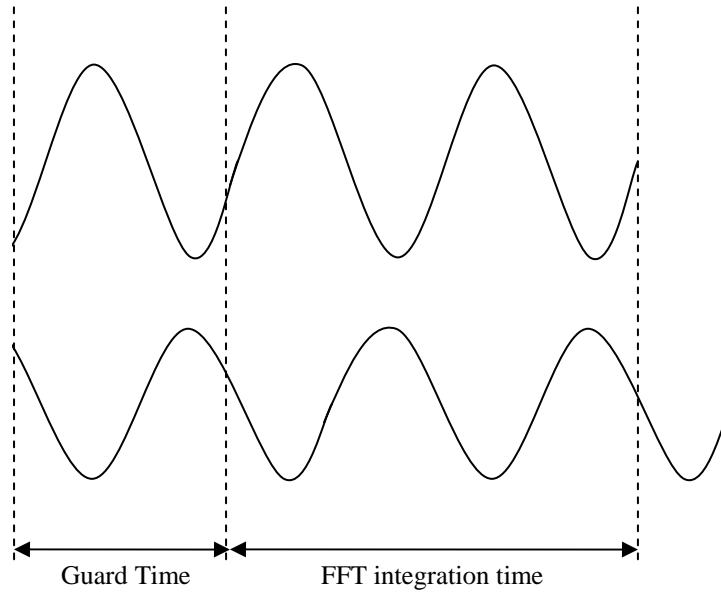
Figure 4.   Delayed sub-carrier with CP (After Ref. [13]).

2.   Synchronization

The receiver of an OFDM communication system must perform an accurate synchronization process. If it is not achieved correctly, the received data will not be reliable due to the effect of ICI and ISI, producing degradation of network performance.

The two main synchronization processes that must be performed in an OFDM receiver are time and frequency synchronization.

A major disadvantage of OFDM signals is the sensitivity to frequency and phase offset. The causes of frequency offset include small differences between the transmitter and receiver carrier frequencies, and the effects of the channel, including Doppler shift. On the other hand, OFDM signals are more robust to time delay, but if this delay is longer than the CP it will yield ICI [13].

The nature of OFDM signals, allows performing synchronization either in the time or frequency domain. Which domain is chosen, will be determined by a trade-off between performance and computational complexity [15].

Most of the synchronization algorithms are based on the use of training sequences (TS), which are specified by the 802.11a standard, known at the receiver, and allow detection of packet presence and computation of the frequency and phase of the signal. An important assumption is that because of the fast and short transmission characteristic of a WLAN packet, the channel is considered unchanged during the packet, so the majority of the synchronization is performed in the preamble and used during the whole packet [15].

a.   Packet Detection

The first step in terms of synchronization is to detect the beginning of a valid transmission. This process is called packet synchronization, where the start time of the packet is estimated. Some known algorithms for this purpose can be used, including *Energy Detection* and *Double Sliding Window* (DSW) packet detection [15]. The former calculates the energy within a sliding window of the received signal, which increases

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when a packet is received. A decision is made based on a predefined threshold. In the DSW packet detection case, the energy in two consecutives sliding windows is calculated. The difference yields an impulse when the packet begins. The drawback of the first method is the complexity in setting the energy threshold that decides whether the incoming signal level indicates the start of a valid packet or not. This is largely because the noise power and the signal power are usually not known beforehand.

Although DSW packet detection is a good solution, better results are obtained if known information is considered, taking advantage of the cross-correlation properties that give a result independent of the power. This known information is the Training Sequence (TS). The resulting algorithm is called *Delay and Correlate* [15].

As depicted in Figure 5, the first step of the algorithm consists of delaying by D samples a copy of the received digital signal r_n, where D is the length of the TS. Then the square of the cross-correlation between the original signal and the delayed version is calculated and divided by the square of the latter, obtaining a normalized result u_n.
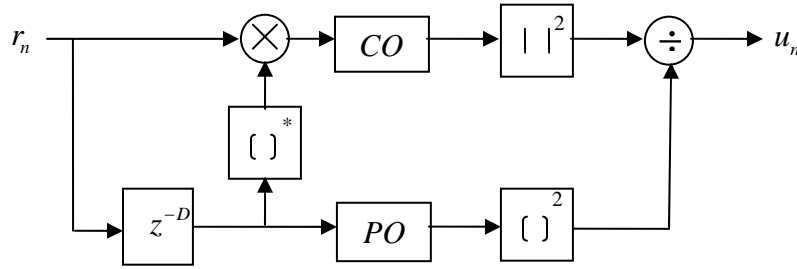
Figure 5.   Block diagram of the *delay and correlate* algorithm (From Ref. [15]).

The terms *CO* and *PO* are computed within a sliding window. The first represents the correlation between the two versions of the incoming signal; the second, the power of the delayed version.

As a consequence, when only noise is received, the correlation averages to zero, but when a valid signal is received, the cross-correlation of the TS gives an increasing value that indicates the presence of the packet.

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b.   *Symbol Timing*

After obtaining a rough estimate of the packet start time, an accurate result is desired. The goal of symbol timing is to find out the exact sample time n when each OFDM symbol starts. A simple way to accomplish this is to determine the exact packet start time and then use the known packet format to determine the start time for each symbol. This is done using a cross-correlation between the incoming signal and the known TS. Figure 6 depicts the corresponding signal flow structure. In this scheme, r_n represents the incoming signal, and g_k the long training sequence.
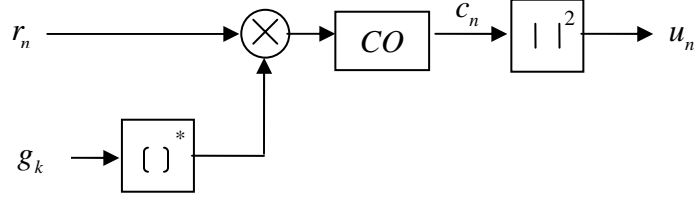
Figure 6.   Block diagram of correlation based algorithm.

The term CO is the corresponding sliding window that computes the cross-correlation indicated below

$$c_n = \sum_{k=0}^{L-1} r_{n+k} g_k^*$$
(2)

As indicated in the equation above, increasing L yields better results, due to the fact that more information is taken into account, but also increases computation. The maximum value of L is limited by the length of the sequence. This situation is one of the tradeoffs that must be in consideration. Sample n that gives the highest u_n value corresponds to the first sample of the packet.

c.   Frequency Synchronization

As mentioned in [15], there are three types of algorithms for solving frequency synchronization

- Data-aided algorithms,

- Nondata-aided algorithms, and

- Cyclic prefix based algorithms.

The best of the algorithm types suited for WLANs is the Data-aided type, where the known training sequences permit us to obtain the frequency offset before the start of the packet's information payload.

Data-aided algorithms can be applied either in the time or frequency domain, although the former is recommended, since computing the DFT of the symbols increases computation without any advantage over the time domain approach.

Figure 7 depicts the signal flow diagram of the transmitted data t_n, where f_{Tx} and f_{Rx} are the transmitted and received carrier frequencies originated by each local oscillator.

$$\tilde{t}_n \longrightarrow \otimes \xrightarrow{\quad \tilde{x}_n \quad} \otimes \longrightarrow \tilde{r}_n$$

$$e^{j2\pi f_{Tx}nT_s} \qquad\qquad e^{-j2\pi f_{Rx}nT_s}$$
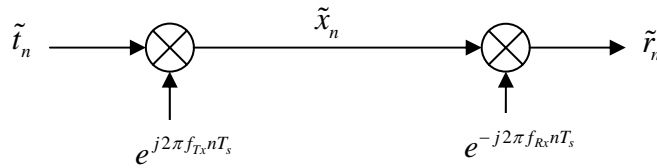
Figure 7.   Analytic signal.

An RF signal

$$x(t) = A(t)\cos(2\pi f_c t + \theta(t))$$

can be represented by its complex analytic signal

$$\tilde{x}(t) = A(t)e^{j[2\pi f_c t + \theta(t)]}$$

Therefore the analytic transmitted signal from Figure 7 can be expressed as

$$\tilde{x}_n = t_n e^{j2\pi f_{tx} n T_s} \tag{3}$$

And the noiseless analytic received signal can be expressed as

$$\tilde{r}_n = \tilde{x}_n e^{j2\pi f_{Rx} n T_s}$$

$$\tilde{r}_n = \tilde{t}_n e^{j2\pi f_\Delta n T_s} \tag{4}$$

where $f_\Delta = f_{Tx} - f_{Rx}$

The frequency offset estimator is calculated after defining the following intermediate variable [15]

$$z = \sum_{n=0}^{L-1} r_n r_{n+D}^* \tag{5}$$

In Equation (5) time delay D is the length of the training sequence, and L is the length of the window used in the cross-correlation.

Substituting for $\tilde{r}_n$ in Equation (5) yields

$$z = e^{-j2\pi f_\Delta D T_s} \sum_{n=0}^{L-1} |t_n|^2 \tag{6}$$

whereby the frequency offset is estimated as [15]

$$f_\Delta = -\frac{1}{2\pi D T_s} \arg(z) \tag{7}$$

d.   *Carrier Phase Tracking*

Carrier phase tracking is an important task in a WLAN receiver. Its goal is to eliminate the residual frequency error, remaining after applying the frequency correction described in the last section. By enhancing frequency accuracy, constellation rotation is avoided.

A data-aided based solution is used here also. The following type of correction is performed for every symbol, using known information that is transmitted in specific carriers, known as pilot sub-carriers or pilot tones. These pilots are going to be affected by the channel, thus the phase difference between the transmitted and received pilots needs to be calculated in order to perform the corresponding correction.

The sent pilot, $P_{s,b}$, and the received pilot, $W_{s,b}$, are related by

$$W_{s,b} = P_{s,b} H_b \tag{8}$$

where s is the symbol index, b is the pilot index, and H_b is the frequency response of the pilot sub-carrier. However, the estimated channel frequency response $\hat{H}_b$ is not perfect and therefore

$$\hat{H}_b = H_b \alpha_b \tag{9}$$

where $\alpha_s = |\alpha| e^{j2\pi s f_\delta}$, and $2\pi s f_\delta$ accounts for all the phase errors in $\hat{H}_b$. Using the estimated channel frequency response, we can calculate an estimated pilot

$$\hat{W}_{s,b} = P_{s,b} \hat{H}_b \tag{10}$$

We can determine the error in the phase of this estimate, and thereby the error in the phase of our channel frequency response estimate by using the actual and estimated received pilots

$$\hat{\theta}_s = \arg\left(\sum_{b=1}^{B} \hat{W}_{s,b} W_{s,b}^* \right) \tag{11}$$

$$= \arg\left(\sum_{b=1}^{B} P_{s,b} H_b (P_{s,b} \hat{H}_b)^* \right)$$

$$= \arg\left(\sum_{b=1}^{B} |P_{s,b}|^2 H_b \hat{H}_b^* \right)$$

Since $|P_{s,b}|^2$ is one, according to the standard, the error in the phase estimate is

$$= \arg\left(\sum_{b=1}^{B} H_b \hat{H}_b^* \right)$$

$$= \arg\left(\sum_{b=1}^{B} H_b (H_b \alpha)^* \right)$$

$$= \arg\left(\alpha^* \sum_{b=1}^{B} |H_b|^2 \right)$$

$$= -\arg(\alpha) \qquad\qquad (12)$$

After the packet is corrected for the estimated channel, it must be further rotated by $-\arg(\alpha)$ to correct for inaccurate phase measurement of H_b.

e.   *Channel Estimation*

A transmitted signal is affected by the channel and noise, as shown in the frequency domain representation shown below

$$E_k = H_k G_k + W_k \qquad\qquad (13)$$

where $k = 0,...., N-1$ and N is the index of the sub-carrier.

E_k: Received Training Sequence (TS).

G_k: Known transmitted TS.

H_k: Channel frequency response.

W_k: Noise.

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A simple way to obtain the channel estimation is as follows

$$\hat{H}_k = E_k G_k^*. \tag{14}$$

Substituting (13) into (14) we obtain

$$\hat{H}_k = \left(H_k G_k + W_k \right) G_k^* \tag{15}$$

$$= H_k \left| G_k \right|^2 + W_k G_k^* \tag{16}$$

The TS values are one or minus one; hence $\left| G_k \right|^2$ is equal to one and

$$\hat{H}_k = H_k + W_k G_k^* \tag{17}$$

Thus the channel estimation represents the effect of the channel and the noise over the transmitted signal.

Using the average of two received TS, the computation of $\hat{H}_k$ can be improved, because the noise terms will partially cancel while the channel term should be essentially static.

$$\hat{H}_k = \left(\frac{E1_k + E2_k}{2} \right) G_k^* \tag{18}$$

C.   IEEE 802.11A

The 802.11a standard is one of a series of WLAN standards based on IEEE 802.11, which was released in 1997 and is well known as Wi-Fi. The original version specifies a maximum data rate of 2 Mbps, using infrared signals or radio spread spectrum at 2.4 GHz. The first amendment proposed was 802.11a, with a maximum data rate of 54 Mbps but operating in the 5 GHz band using Orthogonal Frequency Division Multiplexing (OFDM). The second amendment proposed was 802.11b, with a maximum data rate of 11 Mbps, operating at 2.4 GHz. The 802.11g amendment of this standard was the third amendment of the physical layer. Using the 2.4 GHz band, 802.11g can achieve data rates of 54 Mbps through OFDM and spread spectrum modulation.

This section describes some aspects of 802.11a, needed to understand the manner in which the synchronization algorithms were implemented. The reader should recognize that much of this work can be extended to 802.11g, with few changes.

1.   Modulation Scheme

802.11a uses OFDM, a multi-carrier modulation scheme. The length of the IFFT window is 64 points, where 48 sub-carriers carry user data, four are pilot tones, and the remaining 12 are null tones. The null tones provide a guardband at both high and low ends of the signal spectrum and eliminate the center sub-carrier, which suffers from self mixing in some common hardware implementations. After applying the IFFT to generate the time domain OFDM symbol to be transmitted, the last 16 time domain samples are copied at the beginning of the symbol, yielding a total of 80 time samples per OFDM symbol.

Table 1 shows the possible data rates and bits per OFDM symbol used in 802.11a, depending upon the different modulation schemes and coding rates used.

Data Rate	Modulation	Coding Rate	Coded bits per sub-carrier	Coded bits per OFDM symbol	Data bits per OFDM symbol
6	BPSK	½	1	48	24
9	BPSK	¾	1	48	36
12	QPSK	½	2	96	48
18	QPSK	¾	2	96	72
24	16-QAM	½	4	192	96
36	16-QAM	¾	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	¾	6	288	216

Table 1.   Rate Dependent Parameters (After Ref. [17]).

2. Packet Structure

Part 11 of the 802.11 standard [17], particularly the high-speed Physical layer (PHY) in the 5 GHz Band specification, describes the PHY and Medium Access Control (MAC) structure for 802.11a.

a. PHY for OFDM System Description

In order to send an 802.11a frame with minimum dependence on the PHY, the PHY Layer Convergence Procedure (PLCP) is defined, which adds some fields previously by the MAC layer.

The PHY Layer Service Data Unit (PSDU) can be seen as the payload provided by the MAC, which after being taken by the PLCP, is encapsulated in a PLCP Protocol Data Unit (PPDU), as shown in Figure 8.
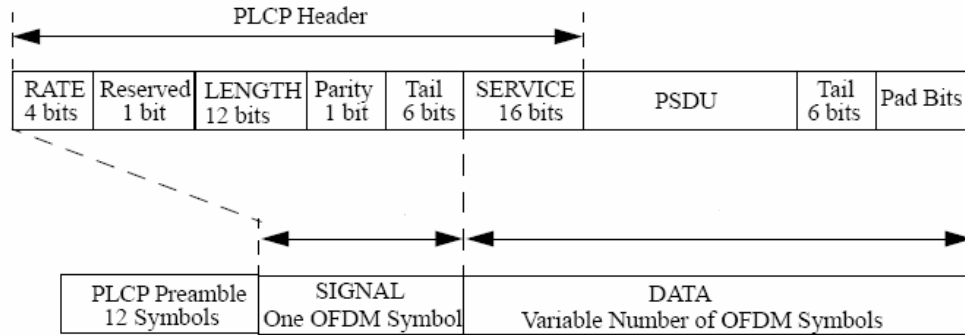
Figure 8.   PPDU frame format. (After Ref. [17]).

The *signal* field consists of one OFDM symbol and is transmitted at the minimum rate of 6 Mbps using BPSK modulation. It contains important information including the rate of the *data* and the length of the PSDU. This field undergoes predefined codification, which includes convolutional encoding, interleaving and pilot insertion. In the codification of the *data* field a scramble step is added.

b. OFDM Specific Service Parameters

In terms of synchronization, the PLCP preamble is a valuable field of the PPDU frame, which contains the TS. It is formed by twelve OFDM Symbols

As depicted in Figure 9 the PLCP preamble contains ten short TSs and two long TSs, wherefore a CP is included.
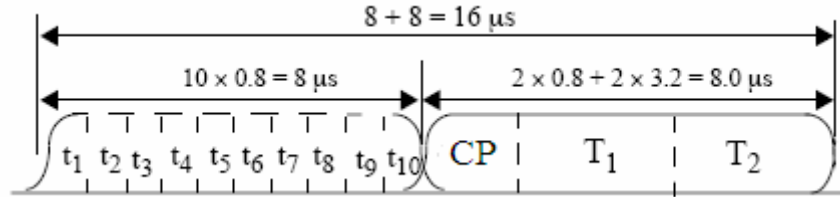
Figure 9.   PLCP preamble. (After Ref. [17]).

Each short TS last $0.8\mu s$ and each long TS last $3.2\mu s$. The group of ten short TSs is denominated the short preamble (SP), and the group of two long TSs plus one CP of $1.6\mu s$ is the long preamble (LP).

Another important features used for synchronization are the pilots. In an 802.11a OFDM symbol, there are four sub-carriers dedicated specifically for carrying a pilot signal, which function was described in II.B.2.d. In order to generate the pilot signal there is a base sequence named P. This sequence has non-zero values only for the sub-carriers indicated in Table 2.

Sub-carrier	Value
-21	1
-7	1
7	1
21	-1

Table 2.   Non-zero values of P sequence.

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The polarity of each pilot sub-carrier change for every symbol, and it is controlled by what is called p_s sequence, which contains 127 values. As an example, the first twelve values are

$$p_s = \{1,1,1,1, \quad -1,-1,-1,1, \quad -1,-1,-1,-1\}$$

where s refers to the symbol index. Thus, for the first symbol, which is the *signal* field, the four sub-carriers are multiplied by one, and for the fifth symbol, the pilot sub-carriers are multiplied by minus one. Therefore, the pilots of the signal field and the fifth data symbol will contain the values indicated in Table 3. The details on how to generate the p_s sequence are described in Reference [17].

Sub-carrier	Signal frame	5th data symbol
-21	1	-1
-7	1	-1
7	1	-1
21	-1	1

Table 3.   Pilot value designation example.

D.   CHAPTER SUMMARY

In this chapter we covered the main concepts behind SDR, OFDM synchronization and the particular case of 802.11a. The next chapter explains the simulations which were performed to verify the correct functionality of the synchronization algorithms, and indicates the principal considerations that should be taken when programming in OSSIE.

III.   SIMULATIONS AND DESIGN

A.   MATLAB SIMULATION

The first step before developing the application was the verification of the corresponding algorithms, which are involved in the synchronization process. For this purpose, the software Matlab was chosen, since many required functions are already developed and the vector and matrix oriented mathematics, make this software ideal for simulations. Additionally, Matlab has a very good debugging tool, which helps to reduce the time spent in finding errors.

The program consists of a main program, named *80211a.m*, divided in three principal blocks, which are depicted in Figure 10. These three blocks are composed of functions that are called as required.

Figure 10.   Block diagram of the Matlab simulation program.

1.   Transmitter

The transmitter generates one 802.11a packet following the specifications indicated in the standard. The first step is the data generation, which consists of random data modulated either in BPSK or QPSK. Then the LP and SP are created.

The *signal* frame is generated through a developed function, which includes CP and pilot tones. The data is arranged by means of another function that also generates the pilot tones. Next, the OFDM symbols are formed, taking the IFFT and adding the CP, according the corresponding position of each sub-carrier, as indicated in Table 4.

Matlab index	Block order	Freq	Block order	Before IFFT	After IFFT	time + CP	Standard index	Matlab Index
1		-26		0	0	48	0	1
2		-25		1	1	49	1	2
3	1	-24		2	2	50	2	3
4		-23	4	3	3	51	3	4
5		-22		4	4	52	4	5
6		-20		5	5	53	5	6
7		-19		6	6	54	6	7
8		-18		7 (1)	7	55	7	8
9		-17		8	8	56	8	9
10		-16		9	9	57	9	10
11		-15		10	10	58	10	11
12	2	-14		11	11	59	11	12
13		-13		12	12	60	12	13
14		-12		13	13	61	13	14
15		-11	5	14	14	62	14	15
16		-10		15	15	63	15	16
17		-9		16	16	0	16	17
18		-8		17	17	1	17	18
19		-6		18	18	2	18	19
20		-5		19	19	3	19	20
21	3	-4		20	20	4	20	21
22		-3		21 (-1)	21	5	21	22
23		-2		22	22	6	22	23
24		-1		23	23	7	23	24
25		1	6	24	24	8	24	25
26		2		25	25	9	25	26
27		3		26	26	10	26	27
28	4	4		27	27	11	27	28
29		5		28	28	12	28	29
30		6		29	29	13	29	30
31		8		30	30	14	30	31
32		9		31	31	15	31	32
33		10		32	32	16	32	33
34		11		33	33	17	33	34
35		12		34	34	18	34	35
36	5	13		35	35	19	35	36
37		14		36	36	20	36	37
38		15		37	37	21	37	38
39		16		-26	38	22	38	39
40		17		-25	39	23	39	40
41		18	1	-24	40	24	40	41
42		19		-23	41	25	41	42
43		20		-22	42	26	42	43
44		22		-21 (1)	43	27	43	44
45		23		-20	44	28	44	45
46	6	24		-19	45	29	45	46
47		25		-18	46	30	46	47
48		26		-17	47	31	47	48
				-16	48	32	48	49
				-15	49	33	49	50
			2	-14	50	34	50	51
				-13	51	35	51	52
				-12	52	36	52	53
				-11	53	37	53	54
				-10	54	38	54	55
				-9	55	39	55	56
				-8	56	40	56	57
				-7 (1)	57	41	57	58
				-6	58	42	58	59
				-5	59	43	59	60
			3	-4	60	44	60	61
				-3	61	45	61	62
				-2	62	46	62	63
				-1	63	47	63	64
						48	64	65
						49	65	66
						50	66	67
						51	67	68
						52	68	69
						53	69	70
						54	70	71
						55	71	72
						56	72	73
						57	73	74
						58	74	75
						59	75	76
						60	76	77
						61	77	78
						62	78	79
						63	79	80

Table 4.   Sub-carriers position of OFDM symbols (After Ref. [17]).

In Table 4, the carriers are divided into blocks, each with a particular number and color, in order to show their correct position, before computing the IFFT. After the IFFT, the last 16 values have a different color to illustrate that these are the CP and, as explained before, added at the beginning of the symbol.

Finally the transmitter concatenates the preambles, signal frame and data frame, in order to form the packet and upconvert it to an arbitrary carrier frequency.

The developed functions for this part of the program are indicated in Table 5.

Function	Description
Signal_frame()	Generates the signal frame in the frequency domain.
Data_frame()	Generates the data frame in the frequency domain.

Table 5.   List of functions defined in the Tx block.

2.   Channel

This section of the simulation program is intended to affect the signal as in a WLAN environment. To accomplish this, Additive White Gaussian Noise (AWGN) is added to the signal, as well as a small frequency variation as might be caused by Doppler shift, and multipath. These functions are indicated in Table 6.

Function	Description
Frequency_offset()	Generates a frequency offset in the carrier frequency.
AWGN()	Add AWGN to the signal.
Multipath()	Includes more than one path to the transmission.

Table 6.   List of functions defined in Channel block.

In order to simulate a multipath environment, the *Multipath()* function includes the Matlab function *rayleighchan()*, where the time delay and the gain of the different paths are defined.

3.   Receiver

The receiver section starts by downconverting the transmitted signal to baseband. Then it follows the block diagram depicted below, which contains the seven functions listed in Table 7.
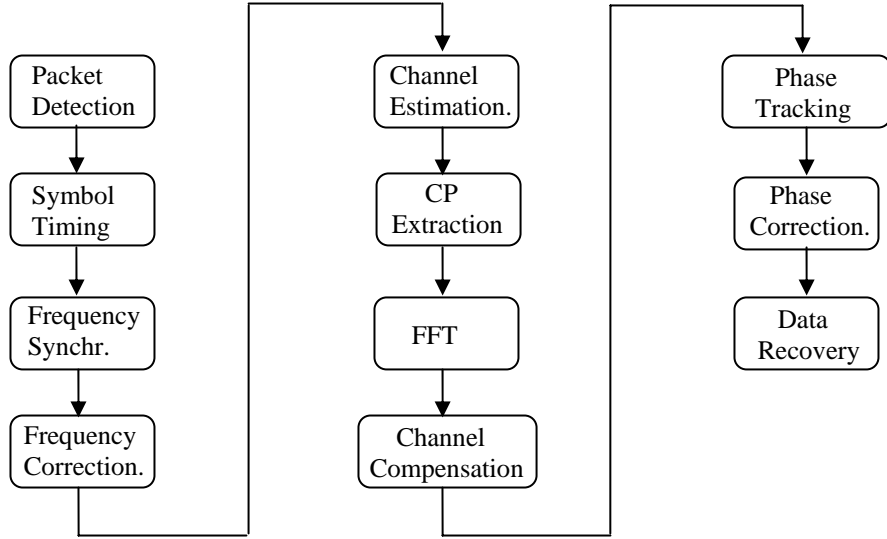

Figure 11.   Received signal after downconversion.

The majority of the involved synchronization algorithms were developed in the time domain, with the exception of the *phase tracking* algorithm, which was performed in the frequency domain.

Function	Description
Delay_Corr_Packet_SYN()	Detects estimated packet start.
Symbol_Timing()	Gives the sample where the packet starts.
Time_Domain_Frequency_SYN()	Obtains frequency offset.
Frequency_Correction()	Applies frequency correction.
Channel_Estimation()	Gives the estimated frequency response of the channel (time domain)
Phase_Tracking()	Computes phase difference between the transmitted and received pilot tones
Data_Recovery()	Obtains the data.

Table 7.   List of functions defined in the Rx block.

The *Delay_Corr_Packet_SYN()* function performs the algorithm discussed in II.B.2.a. This function needs a definition regarding the value of the threshold that indicates that a valid packet is coming. Furthermore, this setting is not enough, since an isolated peak caused by noise could cross the threshold. Thus, the decision must be made considering more than one cross-threshold value. For this simulation 20 cross-threshold value in a row gave a reliable result, empirically based. It is expected that this value depends on noise environment.

The *Time_Domain_Frequency_SYN()* and *Frequency_Correction()* functions are used sequentially more than once, in order to determine the best performance using either the SP or LP. These functions accomplish the algorithms indicated in II.B.2.c.

4. Results

In order to prove the algorithms, the signal was subjected to different types of distortions.

a. AWGN

The noise we chose is such that E_b / N_0 is 10 dB. The noisy signal is

$$y = x + sig \bullet N \tag{19}$$

where: x: original signal.

y: noisy signal.

N: noise of zero mean and unit variance.

$$sig = \sqrt{\frac{mean(x^2) \bullet W}{E_b / N_0 \cdot R_d}} \tag{20}$$

In (20) the bandwidth W is a fixed value of 312.5 kHz, regardless the modulation scheme used. The data rate R_d is set to 6 Mbps for the BPSK case, and 12 Mbps for QPSK.

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b.   *Frequency Offset*

As described in [15], the applied algorithm allows a limited frequency error, defined by

$$|f_\Delta| \le \frac{1}{2DT_s} \tag{21}$$

where D is the length of the TS.

The expected maximum frequency offset using the SP is 625 kHz, and using the LP is 156.25 kHz. On the other hand, the maximum error allowed by the standard is 212 kHz.

Different values of frequency error were applied, verifying the last paragraph, and the algorithm's functionality. Although use of LP can correct a smaller range of offset frequencies, it gives a more accurate result. Thus, a recommended alternative [15] is to calculate a coarse frequency offset with the SP (which has a better operational range), correct the LP, and finally estimate a fine frequency offset using the LP. The next example consists of computing the frequency offset of a BPSK signal, already affected by noise.

Figure 12 depicts the case where a 140 kHz offset is applied. It is noted that the second stage is not needed, since the LP method computes an accurate offset in the first stage. In Figure 13, an applied 170 kHz offset does not allow the LP method to compute a reliable offset in the first stage, thus a frequency correction is applied using the coarse result obtained by the SP method. Now, a second stage using the result utilizing the LP, can enhance the accuracy of the frequency offset.
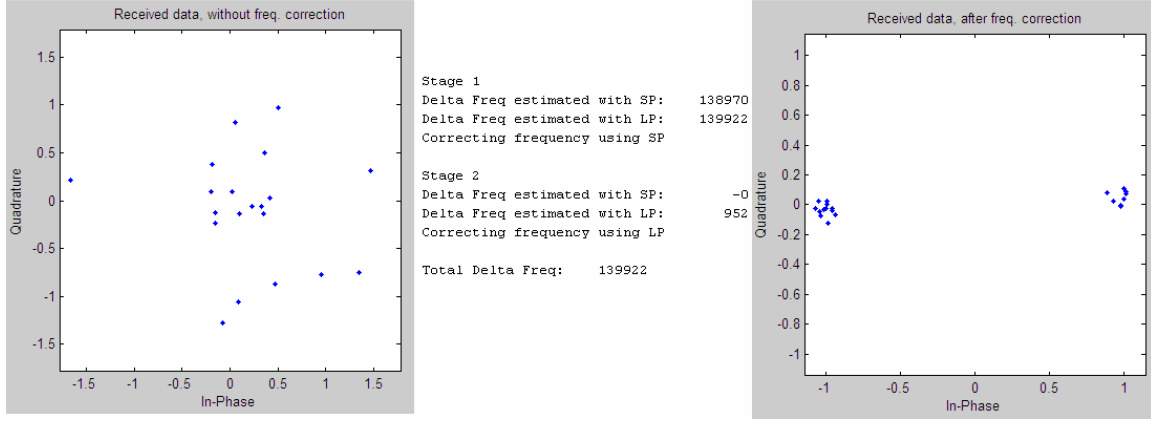
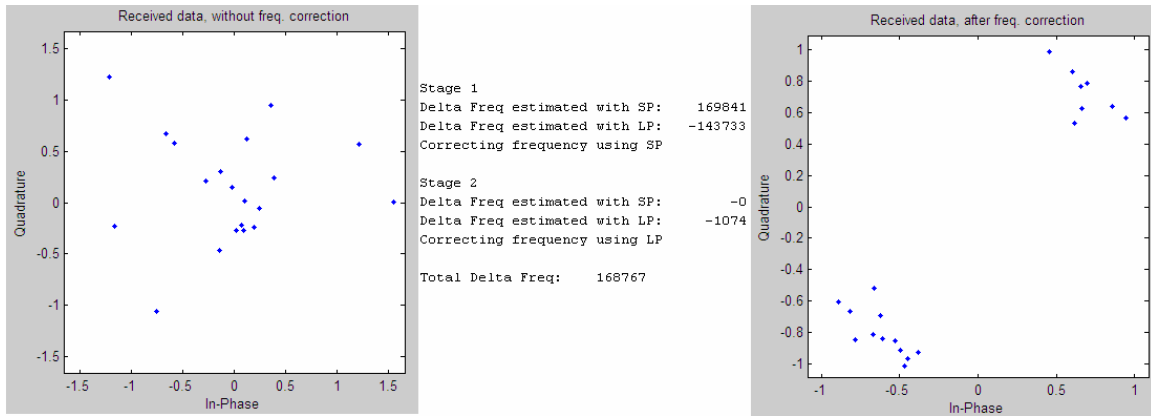Figure 12.   Signal affected by a frequency offset of 140 kHz.

Figure 13.   Signal affected by a frequency offset of 170 kHz.

The rotation noted in Figure 13, is a typical residual phase rotation, which affects the phase of every symbol, before phase tracking is applied.
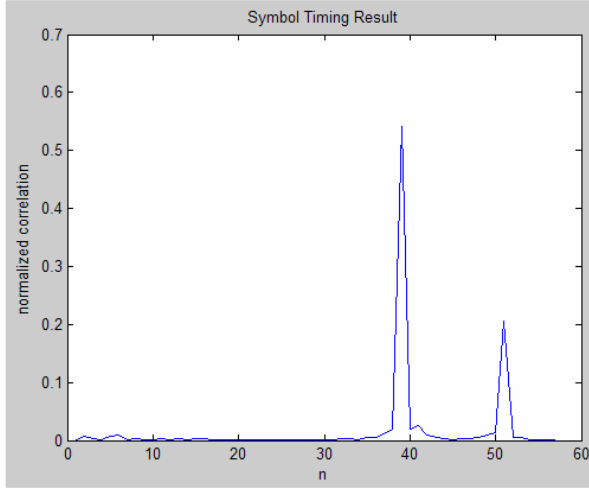
c.   Multipath

In order to perform the simulation of multipath, as in a real WLAN environment, the Matlab *rayleighchan( )* function was used. The goal of the next example is to show how a multipath larger than the CP length, which is $0.8\mu s$ according to Equation (22), begins affecting the signal, producing ISI.

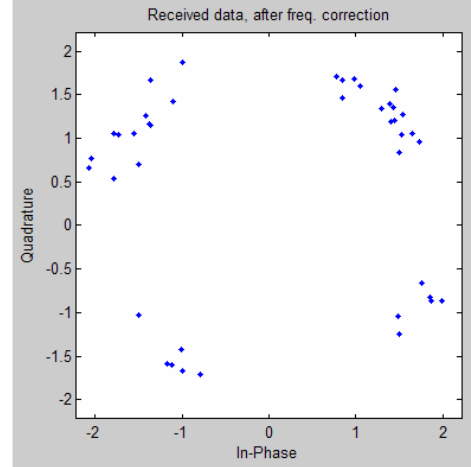$$CP_{length} = \frac{\#samples}{f_s} = 0.8\mu s \tag{22}$$

where $\#samples = 16$ and $f_s = 20MHz$. The evaluation uses a noisy QPSK signal with a frequency offset of 30 kHz and a second path delayed by $0.6\mu s$, in a first experiment, and $1.2\mu s$ in a second one. The correction is performed in three steps:

1. Frequency correction using preambles correlation.

2. Channel correction after estimating the channel.

3. Residual phase correction using phase tracking algorithm.

Figure 14 shows the case where a $0.6\mu s$ multipath is applied. In (a) it is possible to appreciate both paths when the preambles are detected, and in (b) the received packet after frequency correction, where each dot represents a received QPSK symbol. Letter (c) indicates zero errors in the receiver after channel and phase correction, and in (d) it is noted that the resulting constellation has an acceptable shape.

Symbol Timing Result

normalized correlation

n

Received data, after freq. correction

Quadrature

In-Phase

(a)

(b)

```
Stage 1
Delta Freq estimated with SP:      49657
Delta Freq estimated with LP:      32010
Correcting frequency using SP

Stage 2
Delta Freq estimated with SP:        -0
Delta Freq estimated with LP:    -17647
Correcting frequency using LP

Total Delta Freq:      32010


Number of errors:          0
```
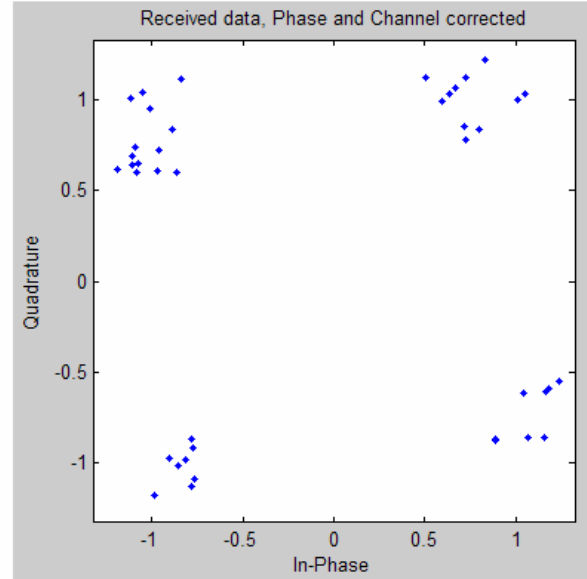
Received data, Phase and Channel corrected

Quadrature

In-Phase

(c)

(d)

Figure 14.   Signal with a second path delayed $0.6\mu s$.

Figure 15, on the other hand, depicts the results after applying a second path delayed $1.2\mu s$, a time larger than the CP. Figure 15(a) shows the distance between paths, and Figure 15(b) the received packet after frequency correction. In Figure 15(c) and (d) we notice some errors as a consequence of the second path's length. This is not surprising. The 802.11a standard is for WLANs which typically are operated indoors. A

path delay of $1.2\mu s$ corresponds to an additional path length of 360 meters. This is an unlikely additional path length to experience in a significant propagation path indoors, so 802.11a is unlikely to experience this problem in its intended application. However, this does suggest that those who wish to use 802.11a equipment outdoors should be aware of the potential problem caused by longer secondary path delays.
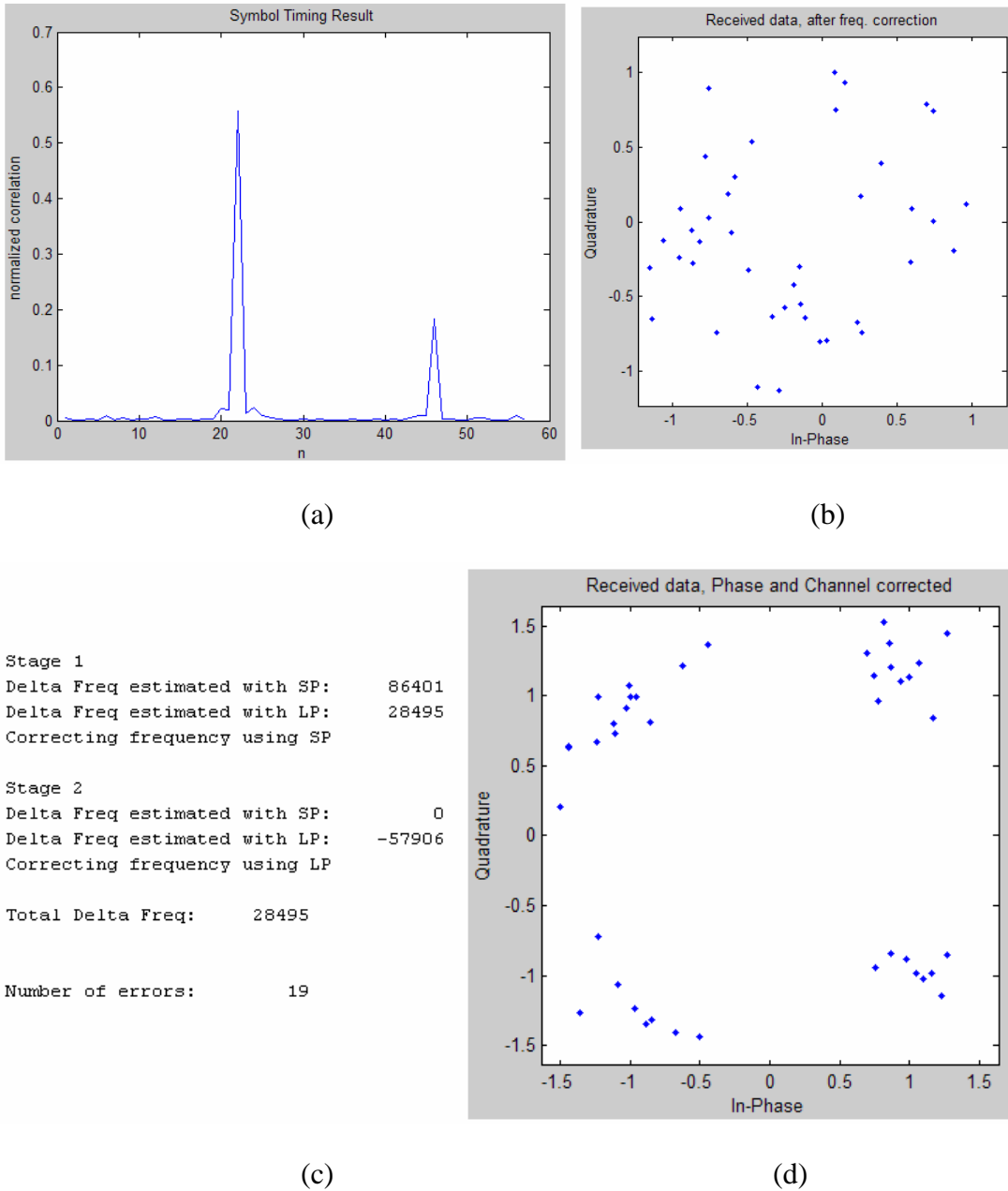

(a)

(b)

(c)

(d)

Figure 15.   Signal with a second path delayed $1.2\mu s$.

B. OSSIE DESIGN

1. Design Considerations

As mentioned before, OSSIE enables the engineer to develop waveforms and components, by using the OSSIE Waveform Developer (OWD). In order to create a waveform, it is necessary to have available the required components. Some helpful features of OWD include the capability to write and edit components, manage ports and include properties.

a. *Components*

An important characteristic of the OWD is the automatic code that is generated when a component is created. This not only allows the component to interact with the rest of the files needed to be installed on a system, but permits the programmer to focus just on the communication task the component should achieve.

After creating a component, the second step is to write the code for a specific task. For this purposes, the commented line "// insert code here to do work", within the function *process_data()*, indicates where to locate the code.

The code written by the programmer is located inside a *while()* loop, which is permanently executed while the component is active. This is an important point under consideration when designing components. Usually the loop starts with a specific function, which allows reading the incoming buffer, getting the data from the previous component. The loop ends by delivering the processed data to the next component and erasing the incoming buffer, leaving it ready to read again.

b. *Ports*

With the release of OSSIE version 0.6.1, the management of ports has been simplified. There are two types of ports: *uses* and *provides*. The first one refers to the port that sends data out of the component and into the core framework (the core framework *uses* the data); the latter, to the component port that receives data from

provided by the core framework. A component can have one, two or more ports. Depending on the application, one of the following basic configurations can be set up.
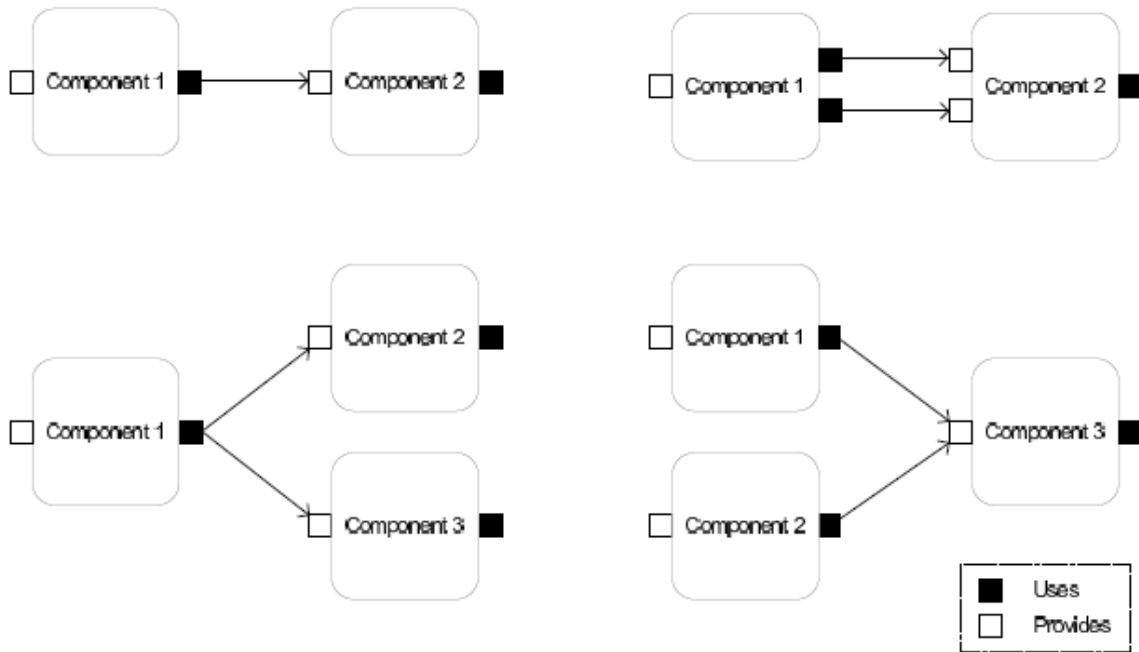

Figure 16.   Sample component communication layouts (From Ref. [18]).

When defining variables, some of them will be initialized at the beginning of the *process_data()* function, outside the mentioned loop. Because a new initialization is needed every time a packet is detected, a second provider port is required in some specific components. This second port is enabled in order to inform such components, that it is time to reset the variables and be prepared to receive a new packet.

c.   Properties

In order to be able to reuse components when creating a waveform, it is desired that the component is developed as general as possible. Under this consideration, the programmer can utilize the same component in different parts of the process, modifying parameters from outside, without the necessity of changing the original component's code. This feature is new with OSSIE, version 0.6.1.

2. Synchronization Components Structure

Following the sequence used in the Matlab simulation, the OSSIE development of 802.11a synchronization keeps the same general structure. Figure 17 shows the block diagram of a waveform that contains the components related with synchronization. It is noted that there are three different block colors. The blue ones represent synchronization algorithms, the yellow ones are the supporting components needed in this configuration, and the red represents a component already developed as part of an earlier thesis. For example, the FFT component is required since some synchronization components work with information based in the frequency domain. An explanation of each particular component is included in the next chapter.
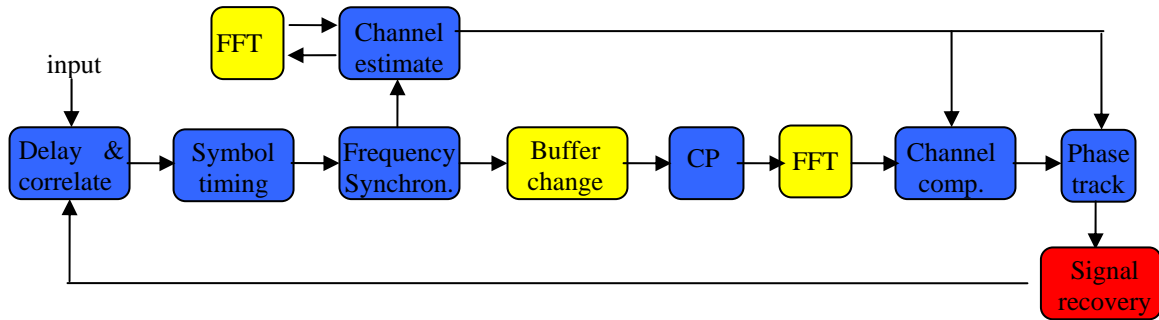

Figure 17.   Block diagram of OFDM synchronization waveform.

The *Signal recovery* component needs to inform the *Delay and correlate* component of the length of the packet, in order to initialize again some particular variables.

So far the general design of the application has been explained, showing the results of the Matlab simulations and indicating the main considerations that should be taken when programming in OSSIE. The next chapter describes in detail each developed component.

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IV.   OSSIE COMPONENT DEVELOPMENT

A.   SYNCHRONIZATION COMPONENT DEVELOPMENT

This section describes the development of each component needed in the synchronization stage of the 802.11a receiver.

1.   Component Development Using OSSIE

In order to create a component, the OSSIE Waveform Developer (OWD) tool should be opened with the following Linux command:

>> python wd.py

Figure 18 shows the Man Machine Interface (MMI) that allows the programmer to create a component. After the component is generated, the following principal files are created automatically:

- ComponentName.cpp

  This is a C++ file which contains the necessary class instances that follow the SCA functionality. This is where the programmer includes the code that will define the component's task.

- ComponentName.h

  This file contains the definition of the classes used by the component.

- Main.cpp

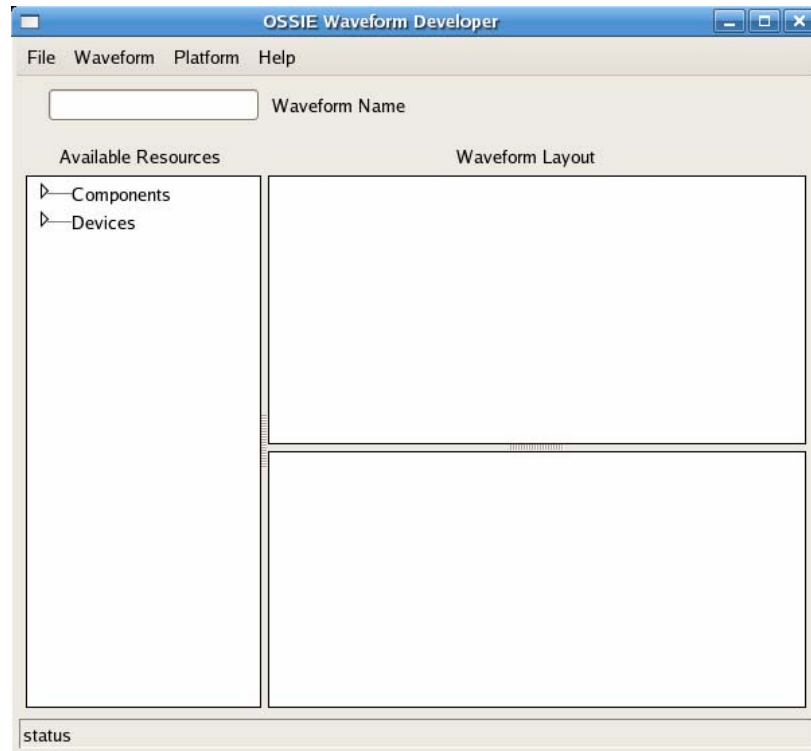 Contains default utility code, transparent to the programmer. [6]

Figure 18.   OWD Man Machine Interface.

The OSSIE version used in this work is 0.6.1. The main differences with respect to the previous version are the following:

- Definition of ports:

    In the old versions, the ports were defined in a separate file. Now the ports are defined in the componentName.cpp file. This change makes the overall development simpler.

- Properties:

    This new feature of OWD allows developers to change the value of specific variables, avoiding the necessity to edit the C++ code to change the variable. This makes the components more general purpose and facilitates software reuse.

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2. Synchronization Stage Components

The further description of the components includes the name of the component, the type of ports used, the properties defined and a flowchart which utilizes the symbols described in Figure 19.
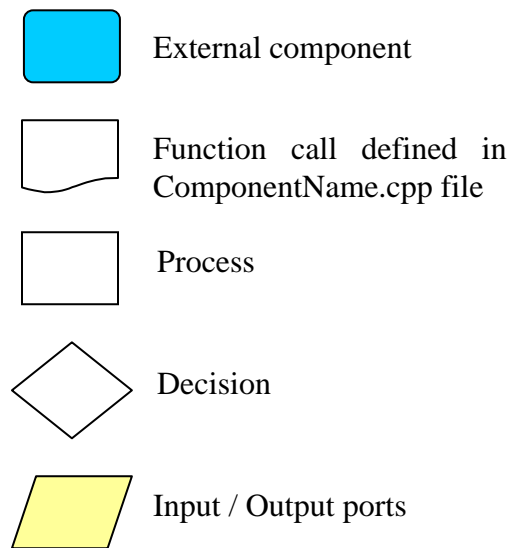

Figure 19.   Flowchart symbol definitions.

The flowchart diagram shows, through a general description, the process accomplished by the method *process_data* mentioned in section III.B.1.a which executes the task of the component.

a.   Delay and Correlate

Component name: Delay_Corr.

Ports:

	Name	**Type**	**Description**
Uses	output_data	complexFloat	Send samples to the next component.
	output_reg	realShort	Ask register for initialization.
	output_ini	realShort	Inform next component whether new packet was detected.
	output_SS	complexFloat	Send two Short Sequences to the next component.
Provides	input_data	complexFloat	Receive samples for processing.
	input_reg	realShort	Receive initialization state.

Properties:

Name	**Type**	**Value**	**Description**
Threshold	Float	0.7	Set the threshold that should be exceeded by a correlation result value, in order to be considered as part of a new packet. Range is between 0 and 1.
Values over Threshold	Short	20	Specify the amount of values that should exceed the threshold sequentially, to decide the presence of a new packet.

Function: This component receives the digital samples either from the digitizer hardware or another component that generates digital samples. In order to facilitate further computation, the length of the data buffer is 128. Its task is to detect a new 802.11a packet using the *delay and correlate* algorithms as discussed in section II.B.2.a and illustrated using Matlab in section III.A.3. When the values that result from the correlation begin increasing and exceed the threshold, this indicates that a new packet is present. Before a packet is detected, all the samples that do not reach the threshold are eliminated, avoiding unnecessary computation for the next component. Because isolated peak values could reach the threshold, a minimum number of them in a row are required. This amount is defined by the *Values over threshold* property. After the packet is detected, all new received data is passed directly to the next component, avoiding unnecessary computation. Figure 20 shows the flow chart that represents the component. Note that an external component named *Initialization* is informed when the reception of the current packet has ended. Its name came from the fact that after a packet has ended, some specific components should initialize variables in order to be prepared to process a new packet. In an OFDM waveform, the *Initialization* component could be fed by another component, whose function is to extract the packet length from the signal frame. If an initialization is required, the *Delay_Corr* component will report this situation to the next component through the *initialization output* port.
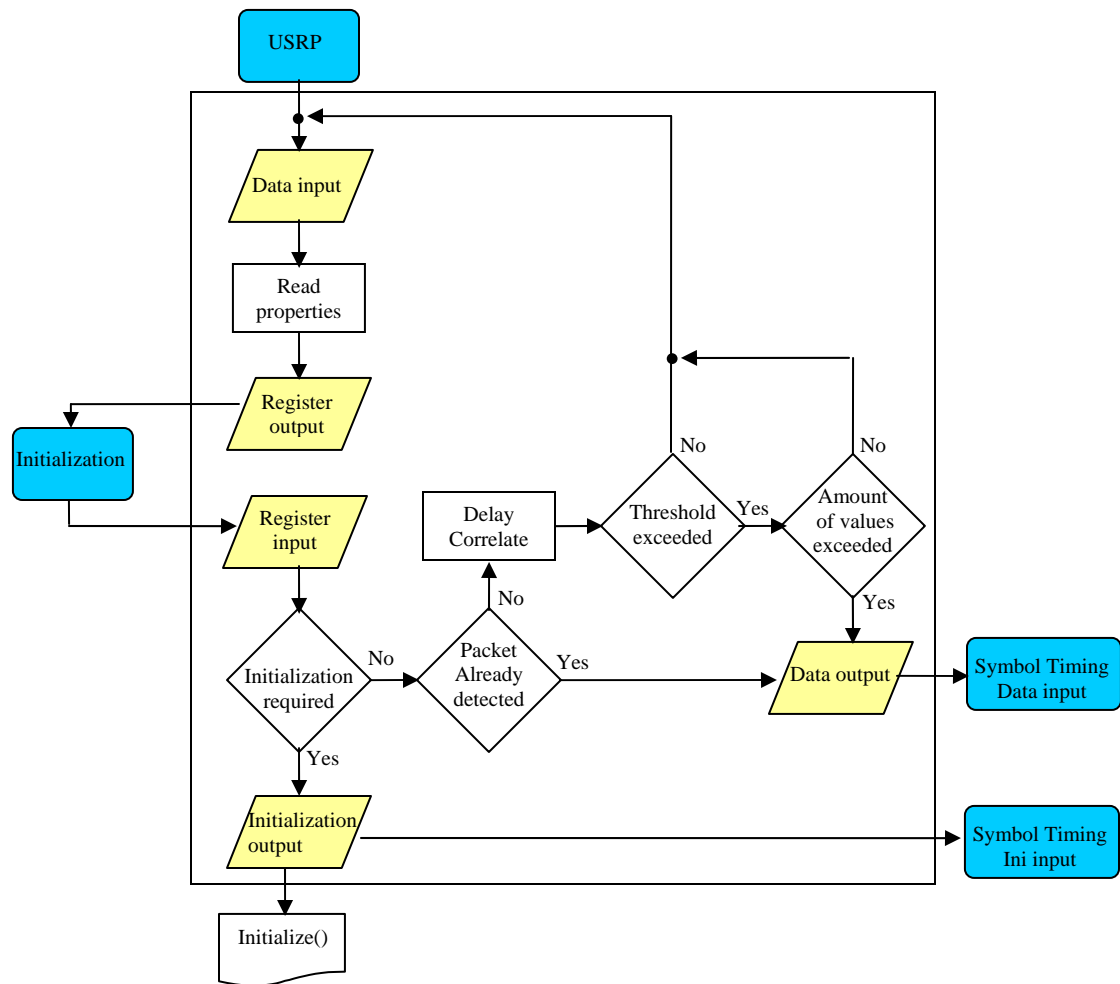
Figure 20.   *Delay_Corr* component flowchart.

b. *Symbol Timing*

Component name: Symbol_Timing

Ports:

	Name	Type	Description
Uses	out_data	complexFloat	Send samples to the next component.
	out_ini	realShort	Inform next component whether new packet was detected.
Provides	In_data	complexFloat	Receive samples for processing.
	In_ini	realShort	Receive initialization state from previous component.

Properties:

Name	Type	Value	Description
Sequence length	Short	64	Set the length of the TS, which will be used in order to compute the corresponding correlation

Function: After receiving the approximate time index for the start of a new packet, *Symbol_Timing* will detect the exact sample, as explained in section II.B.2.b and demonstrated using Matlab simulation in section III.A.3. In order to be able to perform the cross-correlation, the known TS is obtained by reading *I_LS.txt* and *Q_LS.txt* files, as depicted in Figure 21. If the component is used to detect another OFDM standard, both the *Sequence length* property and the aforementioned text files should be changed. This component also must be aware if the current packet ended, since some variables need to be initialized in order to detect the next packet. If the start symbol is detected as a consequence of the cross-correlation, the remainder of the packet is sent to the next component directly, avoiding again unnecessary computations.
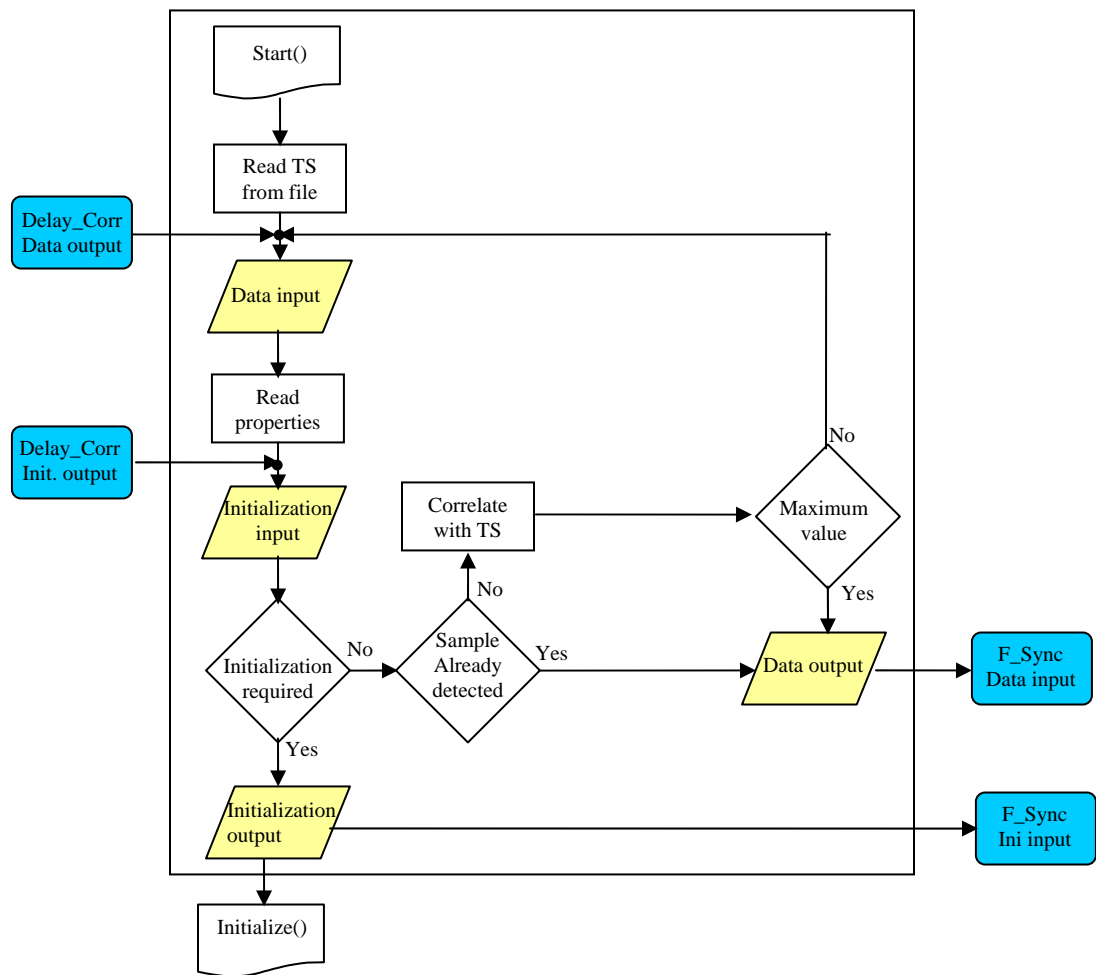
Figure 21. *Symbol_Timing* component flowchart.

c. ***Frequency Synchronization***

Component name: F_Sync

Ports:

	Name	Type	Description
Uses	output_data	complexFloat	Send samples to next the component.
	output_ini	realShort	Inform next component whether new packet was detected.
	output_TS	complexFloat	Send the corresponding TS to the component in charge of channel estimation.
Provides	input_data	complexFloat	Receive samples for processing.
	In_ini	realShort	Receive initialization state from previous component.

Properties:

Name	Type	Value	Description
Sequence length	Short	64	Set the TS length, which will be used to detect the frequency offset.
Fs	Float	20,000,000	Set the sampling frequency in samples per second.

Function: This component detects and corrects the frequency offset of the received packet, as described in II.B.2.c and demonstrated using Matlab simulation in III.A.3. The first received buffer contains both length-64 sequences, thus the frequency offset is only computed in the first loop. Further data inputs from the same packet are only corrected and sent to the *CP* component. The first 128 samples are also corrected

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and then sent to the *Channel_Estimation* component, which needs that information to achieve its task. *F_Sync* also needs to initialize variables every time a new packet will be received. Figure 22 is the flowchart for this component.
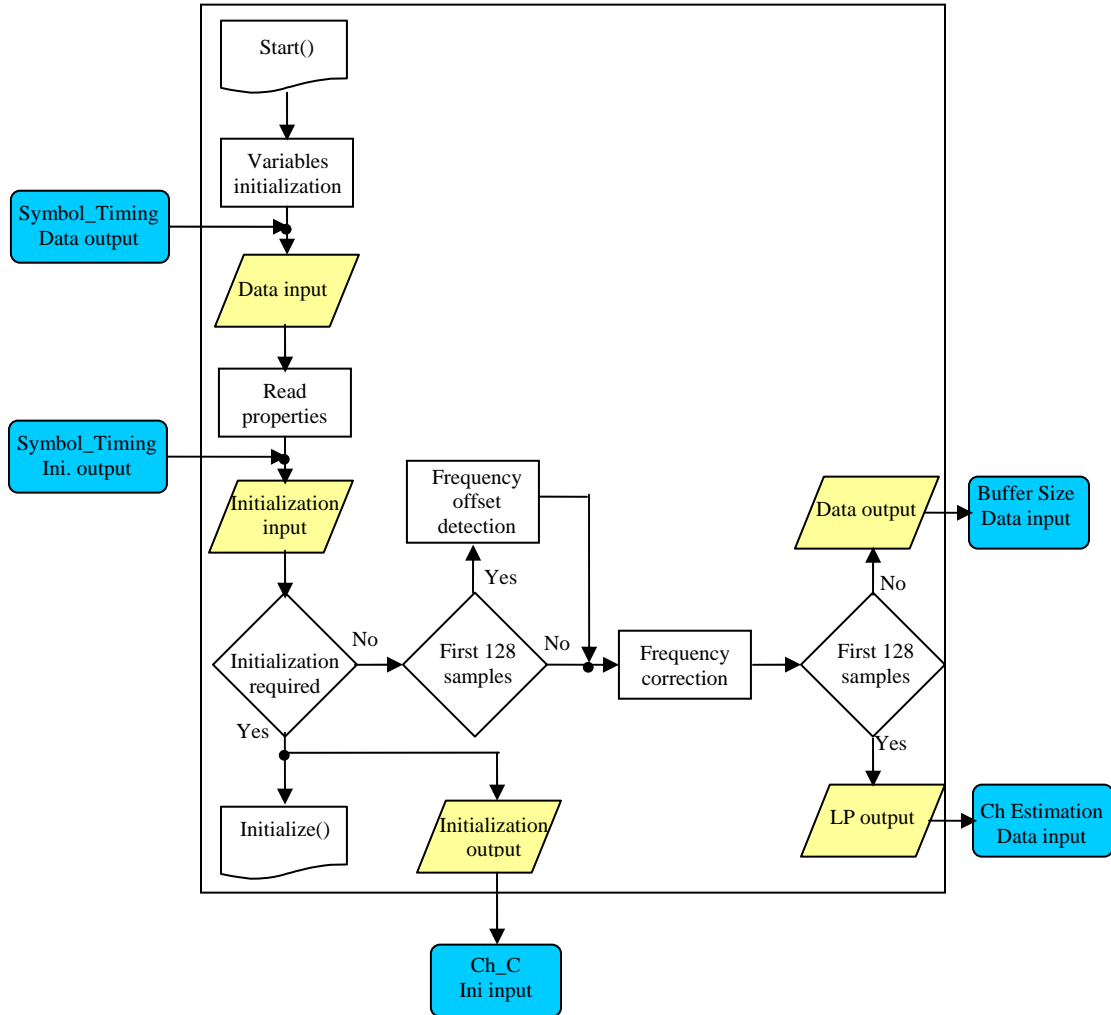
Figure 22.   *F_Sync* component flowchart.

d. **Channel Estimation**

Component name: Channel_Estimation

Ports:

	Name	Type	Description
Uses	output_data	complexFloat	Send the coefficients of the estimated channel.
	output_FFT	complexFloat	Send each TS to obtain the FFT.
Provides	input_data	complexFloat	Receive samples.
	In_FFT	complexFloat	Receive the frequency domain representation of the TS.

Properties:

Name	Type	Value	Description
Sequence length	Short	64	Set the length of the training sequence that will be used to detect the frequency offset.

Function: *Channel_Estimation* receives two sequences of the length specified in *Sequence length* property. The algorithm applied corresponds to the indicated in II.B.2.e and demonstrated using Matlab in III.A.3. Figure 23 shows the functionality of this component. The original training sequence is obtained by reading the text files *I_LSfd.txt* and *Q_LSfd.txt* , which, unlike the files used in *Symbol_Timing* component, these correspond to the frequency domain. Changing the information contained in these files, and the value specified in *Sequence length* property, this component could be used in other standard.
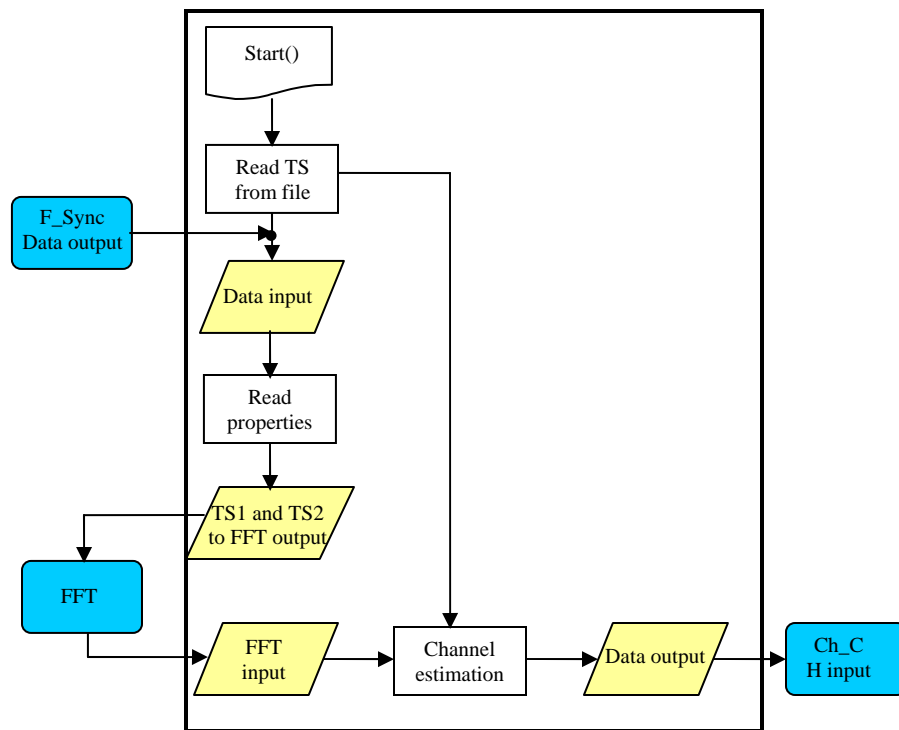
Figure 23.   *Channel_Estimation* component flowchart.

e.   ***FFT***

Component name: fft

Ports:

	Name	**Type**	**Description**
Uses	output_data	complexFloat	Send the frequency representation of the processed data.
Provides	input_data	complexFloat	Receive time samples.

Name	Type	Value	Description
Length	Short	64	Set the length of the FFT.

Function: This component utilizes the open source C++ library named *fftw* [19] which contains the necessary functions for applying the FFT to the incoming signal. The specific function that performs the FFT operation is *fftwf_plan_dft_1d()*, where two arrays of the special type *fftwf_complex* are included. These arrays are named *in* and *out*. The first carries the time samples to be processed and the latter the resulting frequency samples. Other functions delete the variables and liberate the corresponding memory. Figure 24 indicates the different steps executed by the *FFT* component.
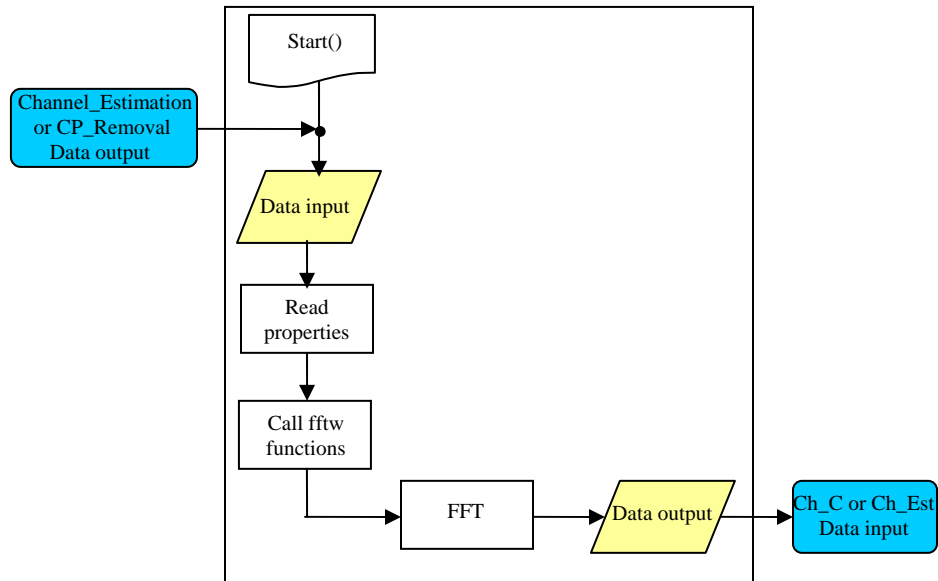

Figure 24.   *FFT* component flowchart.

f.   *Buffer Size*

Component name: Buffer_Size

Ports:

	Name	Type	Description
Uses	output_data	complexFloat	Send samples through a defined buffer length.
Provides	input_data	complexFloat	Receive samples for processing.

Properties:

Name	Type	Value	Description
Out size	short	80	Set the length of the output_data port.

Function: Output_Size is a simple component that changes the length of the output_data port, which accommodates the data size according to the next component function. In the case of the 802.11a waveform developed in this thesis, it is simpler to use a buffer size of 128 samples at the beginning, which is the length of two long TSs, and then change the buffer size to 80, which is the OFDM time symbol length.
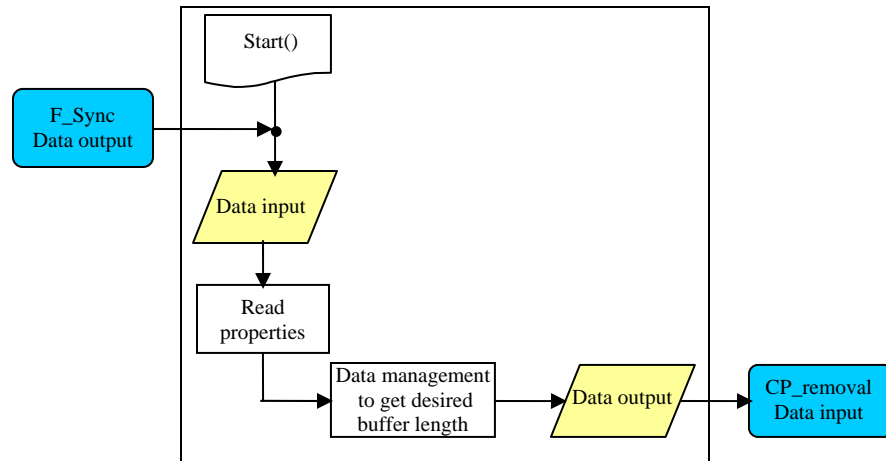
Figure 25.   *Buffer_Size* component flowchart.

g.   CP Removal

Component name: CP_Removal

Ports:

	Name	**Type**	**Description**
Uses	output_data	complexFloat	Send samples after removing the CP.
Provides	input_data	complexFloat	Receive samples for processing.

Properties:

Name	**Type**	**Value**	**Description**
CP Length	short	16	Set the length of the cyclic prefix of each OFDM symbol.

Function: This component is very similar to the *Buffer_Size* component, where the size of the output buffer is going to change, with the difference that

CP_Removal eliminates the truncated portion of data, which correspond to the cyclic prefix. The figure below depicts the corresponding flowchart.
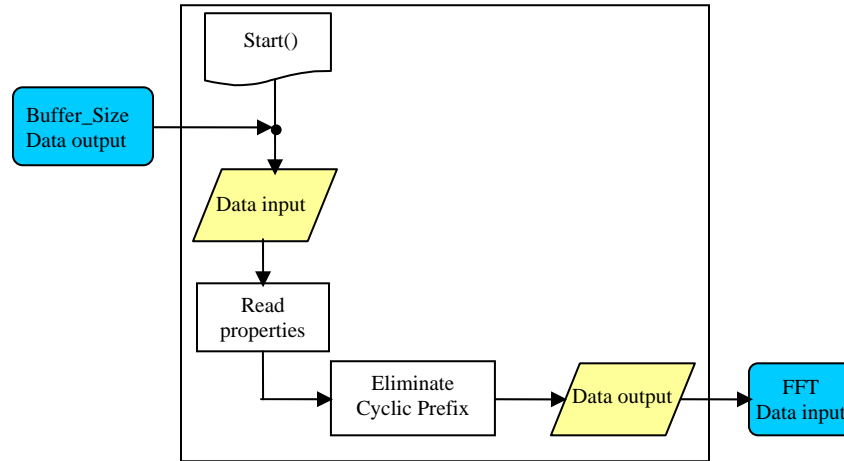

Figure 26.   *CP_Removal* component flowchart.

h.   Channel Compensation

Component name: Ch_C

Ports:

	Name	Type	Description
Uses	output_data	complexFloat	Send corrected samples to the next component.
	output_ini	realShort	Inform next component whether new packet was detected.
Provides	input_data	complexFloat	Receive samples for channel compensation.
	input_ini	realShort	Receive initialization state.
	Input_H	complexFloat	Receive the estimated channel coefficients.

Function: Ch_C, applies the corresponding correction to the whole packet as described in II.B.2.e and demonstrated using Matlab simulation in III.A.3. This

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component also needs to be initialized after the current packet is completely received, in order to start applying the new channel estimate to the new packet, since it assumed the channel does not change during a packet transmission, but could change for the next packet.
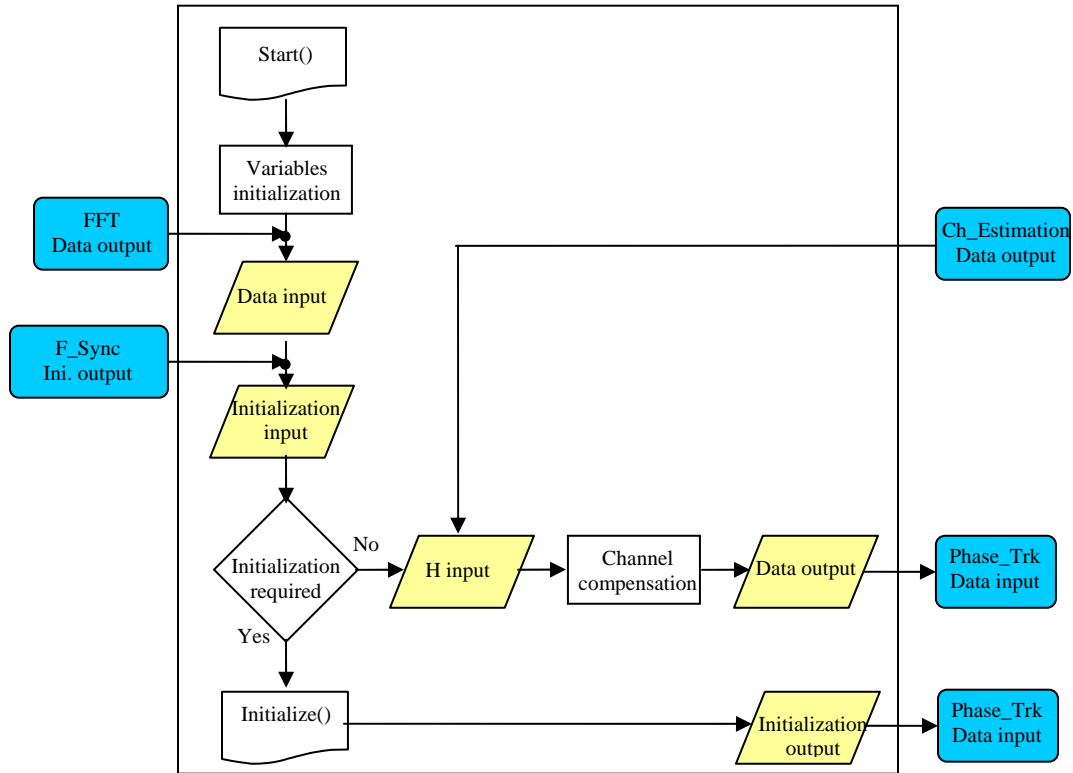

Figure 27.   *CH_C* component flowchart.

Component name: Phase_Trk

Ports:

	Name	Type	Description
Uses	output_data	complexFloat	Send samples after phase correction.
	output_ini	realShort	Inform next component whether a new packet was detected.
Provides	input_data	complexFloat	Receive samples for processing.
	input_ini	realShort	Receive initialization state from previous component.
	Input_H	complexFloat	Receive the estimated channel coefficients.

Function: This component performs the phase tracking described in II.B.2.d and demonstrated using Matlab simulation in III.A.3. Sequence p_s indicated in II.C.2.b is obtained after opening the file *pol_p_seq.txt*. Since this component requires the channel estimated information for each packet, as the *Ch_C* component provides, it should be initialized when a new packet is detected. Figure 28 depicts the corresponding flowchart. It is noted that the component receiving the data from *Phase_trk* should be the *Signal* component, developed by Leong [7]. On the other hand, the *Initialization_output* port is available to be connected to any component that needs a variable initialized, when a new packet is detected.
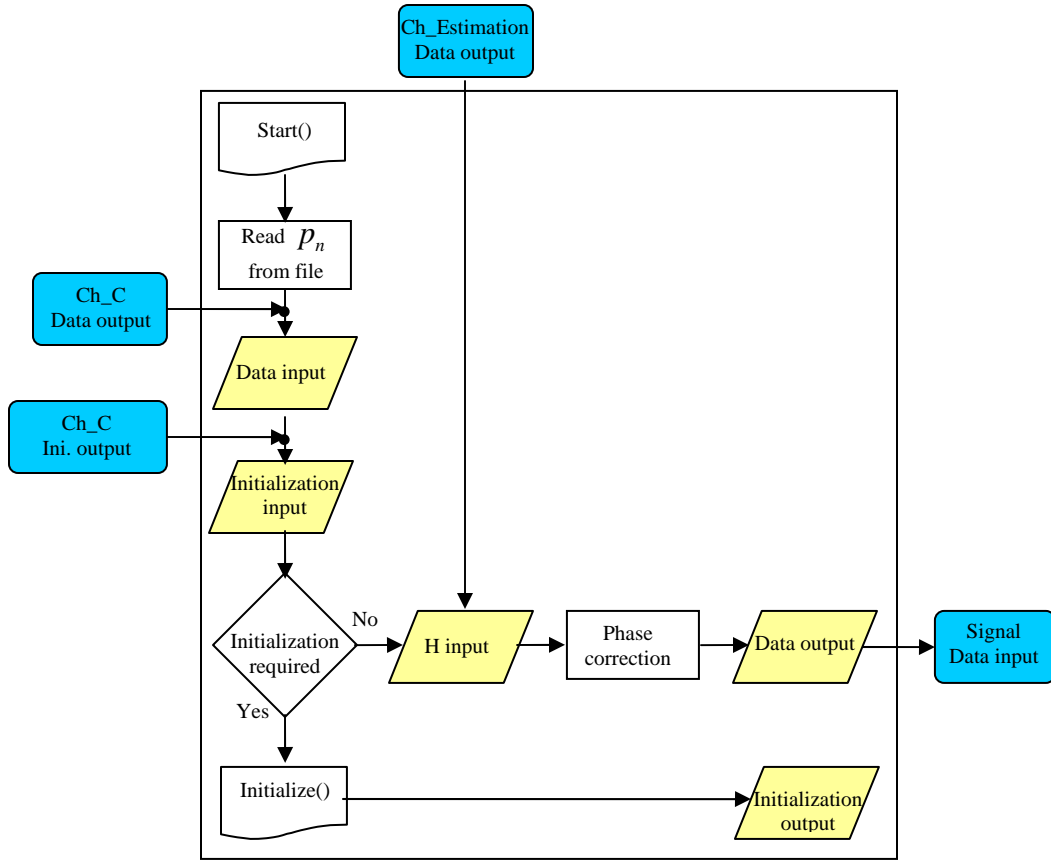
Figure 28.   *Phase_Trk* component flowchart.

B.   ISSUES DURING DEVELOPMENT AND RECOMMENDATIONS

1.   OSSIE Installation

OSSIE can be installed using the Virtual Machine Ware (VM-Ware) player [20], where a complete image of OSSIE can be run within the Windows Operating System (OS). This is a fast and easy installation, but with the limitation of not having complete access to all the resources of the computer. The other alternative is to install OSSIE over the Linux OS, which is known as a native installation.   Considering the fast synchronization requirement and the high data rate of 802.11a, the native installation is the more convenient alternative.   The disadvantage of the native installation is the

complexity in installing all the requested programs and libraries [4], especially if there is a lack of background in working with the Linux OS.

2.   Documentation

Because OSSIE is still under development, there is no complete manual which explains the details of how to program a component. The way to learn it was either by reading code from an existing component, or asking the OSSIE team through an Internal Relay Chat (IRC) channel called #ossie. Reference [4] includes a user guide wherein is described how to connect to the mentioned IRC channel. The following explanations are the solutions to some problems encountered while programming the above-described components.

a.   *Assembly Controller Component*

When developing a waveform using OWD, one specific component should be assigned as the *assembly controller*, The assembly controller starts the sequential process that will activate the rest of the components after sending data through the ports. This assignment is not enough; code must be added in the source (*Component_Name.cpp*) and header (*Component_Name.h*) files, where the additional code is in red:

```
Source file:
        Void ComponentName_i::start()
        Processing_thread = new omni_thread(process_data,(void*) this);
        VariableName_active = true;
        Processing_thead->start();
        Std::cout << "start called" << std::endl;

        Void ComponentName _i::stop()
        VariableName_active = false;
        Std::cout << "stop called" << std::endl;

        Void process_data(void *data)
        .
        .
        while(ClassInstanceName->VariableName_active) {
        ………………………..
```

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```
} //while
ClassInstanceName ->processing_thread->exit();
```

Header file:
```
// list components provides and uses ports
 Bool VariableName_active;
```

b.   FFTW Library

When compiling a library or software in Linux, four command steps are required:

- ./reconf

- ./configure

- make

- su –c "make install"   (as root)

In the case of *fftw*, the following options should be included in the *configure* command step:

./configure --enable-single --enable-shared --enable-threads --enable-float.

A specific library called *lfftw3f* must be included, in order to be able to operate with floating point numbers. If after typing the *make* command at the prompt, the compiler complains about an undefined reference to *fftwf*, the library *–lfftw3f* should be included by typing the following at the command prompt:

```
g++  -Wall  –g  -02  –I/usr/local/include  –pthread  –L/usr/local/lib  –o
ComponentName  ComponentName.o  –lomniORB4  –lomniDynamic4  –
lomnithread  –L/usr/local/lib  –lossieidl  –lossieeparser  –lossieecf  –lfftw3f  –
L/usr/local/lib –lstandardInterfaces
```

Now the library *lfftw3f* (in red) has been added to the rest of the required libraries. This process should be performed any time a component using this library is edited.

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V. 802.11A WAVEFORM AND TESTING

A. 802.11A SYNCHRONIZATION WAVEFORM

The components developed in this thesis form part of a complete core of components needed in an 802.11a receiver. As mentioned in I.C.1, the OSSIE components developed by Leong [7] consider the demodulation and decoding stage of the receiver assuming an ideal channel. In order to design a complete receiver, a front-end is required to obtain the baseband digital samples, as well as the equivalent software component to control the hardware. Therefore, the general structure of the receiver would be as described in Figure 29.
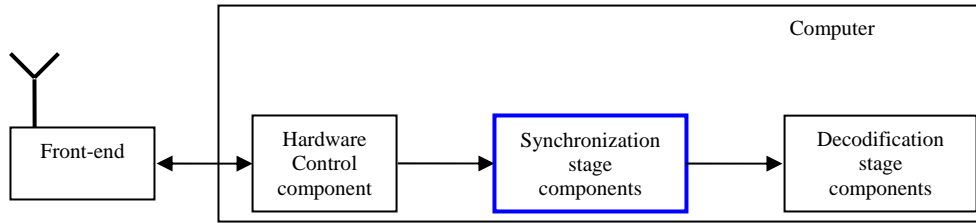
Figure 29. 802.11a component core structure.

After having available all the required components and hardware, the next step is to apply the necessary connections through a waveform, which is developed using the OWD tool from OSSIE. Regarding the synchronization stage, the part of the waveform that achieves this task will receive the digital samples from the hardware control component, and output result samples to the decodification stage components. Figure 30 depicts a simple model of the synchronization part of the waveform, where the components are shown inside the blue block of Figure 29.
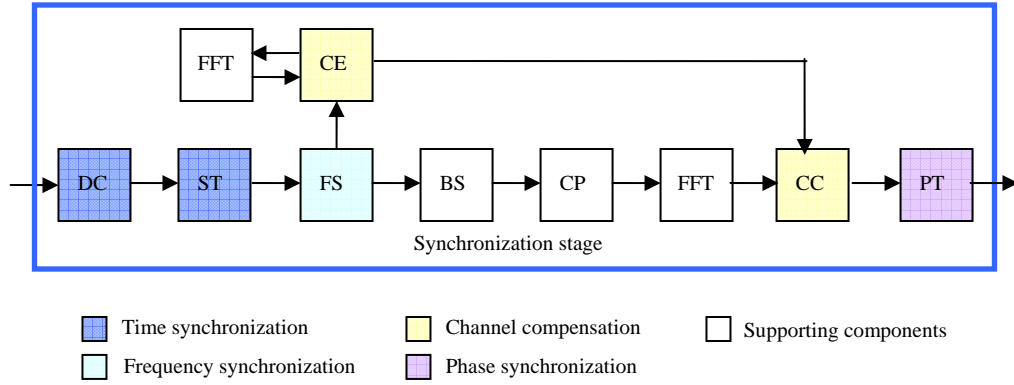
Figure 30.   General model of synchronization stage waveform.

where:

        DC: Delay and Correlate (*Delay_Corr*).

ST: Symbol Timing (*Symbol_Timing*).
FS: Frequency Synchronization (*F_Sync*).
CE: Channel Estimation (*Channel_Estimation*)
FFT: Fast Fourier Transform (*fft*)
BS: Buffer Size (*Buffer_Size*)
CP: CP Removal (*CP_Removal*)
CC: Channel Compensation (*Ch_C*).
PT: Phase Tracking (*Phase_Trk*).

A more complete model is depicted in Figure 31, wherein the waveform includes a coarse frequency synchronization step. It shows in green the components that work in the frequency domain and it indicates the length of the port buffers. Another important characteristic of this waveform is the initialization circuit, depicted through red arrows, whereby the corresponding components become activated when a new packet is detected and therefore specific variables should be initialized. For this purpose, a component named *Initialization_Register* has a register whose value indicates whether an initialization is needed or not. This information is extracted from the *signal* frame, where the length of the packet is contained, by a component from the demodulation and decoding stage.
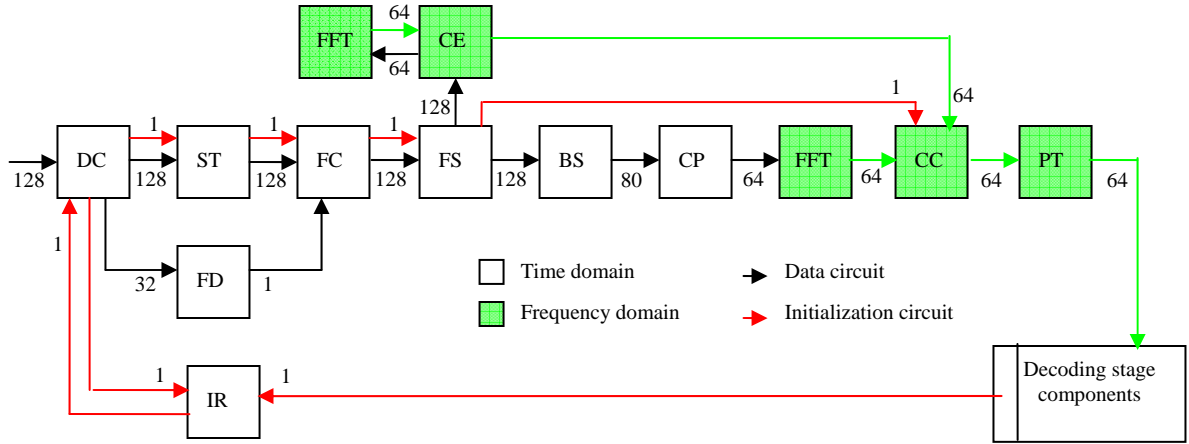
Figure 31.   Initialization circuit.

where:
    FD: Frequency Detection (*Frequency_detection*).
    FC: Frequency Correction (*Frequency_correction*).
    IR: Initialization Register (*Initialization_Register*).

B.   TESTING WAVEFORMS

The ideal testing situation processes real data from the air, through a digitizer. A known board that does this work is denominated the Universal Software Radio Peripheral (USRP), which contains a front end, an Analog to Digital converter (ADC), and a Field Programmable Gate Array (FPGA) containing a decimator that permits the reception of the data at the Intermediate Frequency (IF) using a sample rate defined by the user, within certain constraints. The transmission of the data to the computer, where the components are, is accomplished by a Universal Serial Bus (USB) port. Unfortunately the throughput that 802.11a signals process is greater than the amount of data a USB port can manage. For this reason the testing was achieved utilizing 802.11a data generated by Matlab, simulating noise, frequency offset and multipath.

In order to test the functionality of the components, we needed to develop a series of different waveforms to obtain the processed data of each step within the synchronization task. Each data set was saved in a separate text file. After passing the generated signal over the testing waveforms, the files are then opened by the same

Matlab program that generated the signal. In this program, the results are shown by the corresponding graphs and errors counts obtained after the whole synchronization process. All these waveforms have two extra components for testing purposes. The first is denominated *gen*, which takes the Matlab generated signal, and sends it to the first component in the chain, *Delay_Corr*. The other component is *Rx_Float*, which obtains the digital samples after the whole synchronization process and saves it in the corresponding file, depending upon the waveform under test. The testing waveforms are as follows:

1.   Test 0

This waveform saves the received signal just after time synchronization. Figure 32 shows the corresponding waveform, where the data is saved in *file0.txt*.
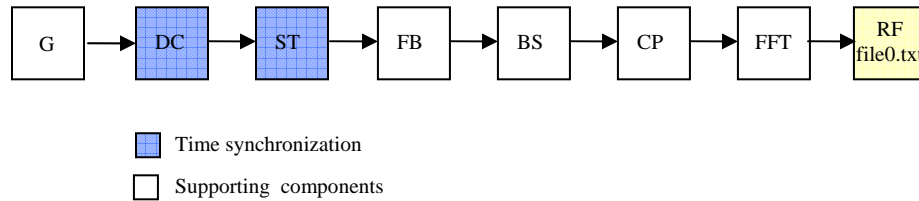
Figure 32.   Test 0 waveform.

where:
G: Generated Signal (*gen*).
RF: Received Signal (*Rx_Float*).
FB: First Buffer Removal (First_Buffer).

Because the *Symbol_Timing* component includes in its first buffer the Long Preamble (LP), a special component is needed for removing these samples and thus saving only *signal* and *data* fields in the file. The component that achieves this is called *First_Buffer*.

2. Test 1

In order to get the packet after a coarse frequency correction using the Short Preamble (SP), the *Test_1* waveform was developed. Figure 33 depicts the corresponding flowchart, where it is indicated that the data is saved in *file1.txt*.
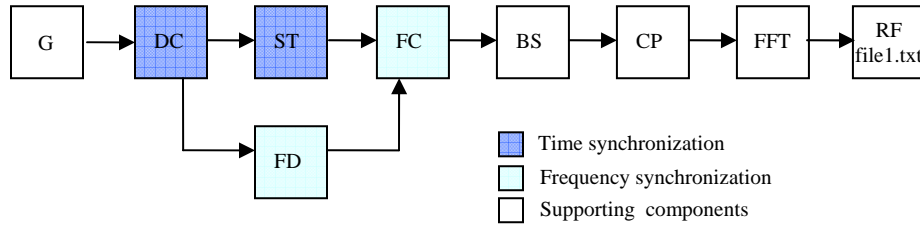

Figure 33.   Test 1 waveform.

3. Test 2

This waveform obtains the signal after fine frequency correction, without a previous coarse correction. The goal of this is to show that for frequency offset less than 156 kHz, as explained in III.A.4.b, a coarse correction is not needed. This is crucial when the signal is undergoing a frequency offset greater than 156 kHz. The digital samples are saved in file2.txt at the input port of *Ch_C*, as shown in Figure 34.
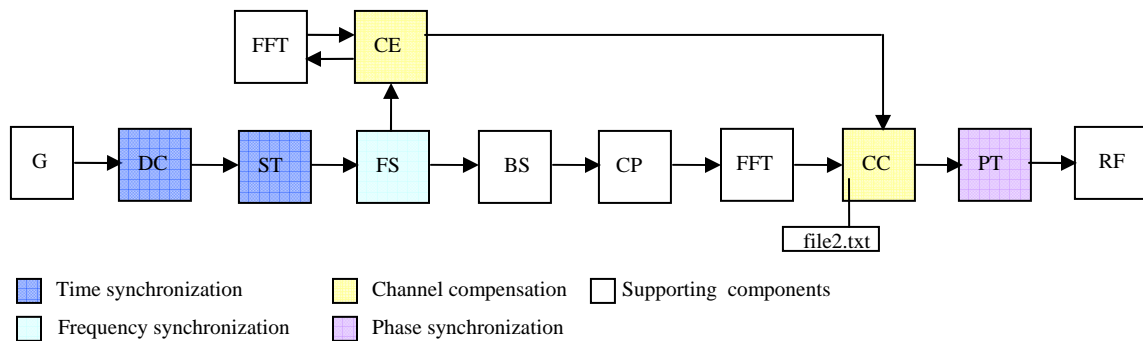
Figure 34.   Test 2 waveform.

4. Test 3

The last waveform required for testing the synchronization stage is *Test_4*, which saves the digital samples after coarse and fine frequency synchronization in *file3.txt*, the result of channel compensation in *file4.txt*, and the received signal after the phase tracking step in *file5.txt*.
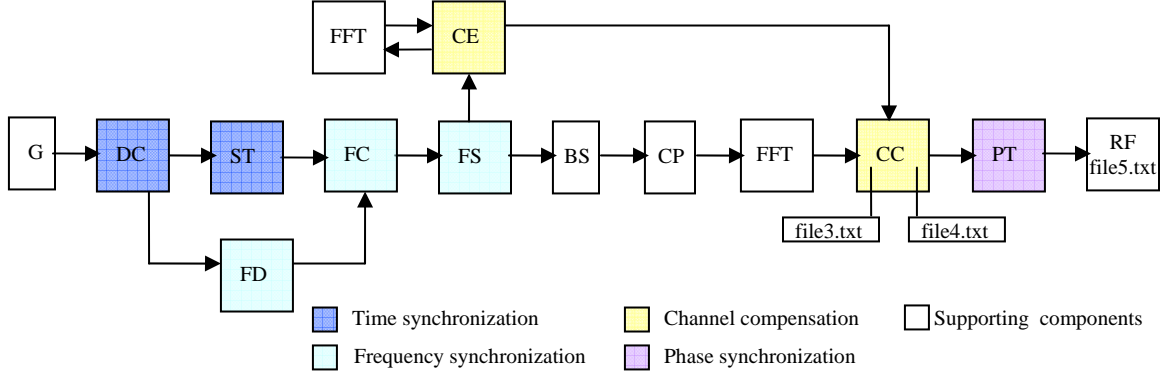
Figure 35.   Test 3 waveform.

C.   RESULTS

The resulting data from each waveform explained in the prior section, is shown using a constellation diagram that indicates the distribution of the digital samples in the I and Q channels of one sub-carrier. A total of six signals were generated to demonstrate the effect of a non-ideal channel, and the corresponding contribution of each component in enhancing the signal. All the signals are preceded by random values, and are affected by noise. Table 8 shows the characteristics of each signal.

Name	Length (Samples)	Modulation	Freq offset [kHz]	2nd Path [μs]	3th Path [μs]	4th Path [μs]
Signal 1	960	BPSK	30	---	---	---
Signal 2	960	BPSK	180	---	---	---
Signal 3	3000	QPSK	180	---	---	---
Signal 4	3000	QPSK	20	0.6	---	---
Signal 5	3000	QPSK	20	1.2	---	---
Signal 6	3000	QPSK	160	0.3	0.5	0.6

Table 8.   Characteristics of the simulated 802.11a signals.

The frequency offset represents the difference between transmitter and receiver local oscillators and the effect of Doppler shift caused by moving devices.

The next description explains each of the testing signals, which include two figures with sub-figures. The first indicates the effect of choosing one or two steps in frequency synchronization, and the latter the result of applying channel and phase correction. The letter distribution of the sub-figures is described below:

First figure:

(a) Received signal after packet detection (*file0.txt*).

(b) Signal after coarse frequency synchronization (*file1.txt*).

(c) Signal after fine frequency synchronization, without a previous coarse frequency correction (*file2.txt*).

(d) Signal after fine frequency synchronization with a previous coarse frequency correction (*file3.txt*).

Second figure:

(a) Signal after channel compensation (*file4.txt*).

(b) Signal after phase tracking (*file5.txt*).

1. Signal 1

The intention of this signal is to demonstrate a simple BPSK transmission affected only by noise and a small frequency offset, which can be managed using only one frequency synchronization step, utilizing the Long Preamble. In Figure 36 it is possible to verify that the coarse frequency synchronization does not enhance the signal as desired. In fact it is not needed by the fine synchronization as depicted in sub-figures (c) and (d), where there is no difference.
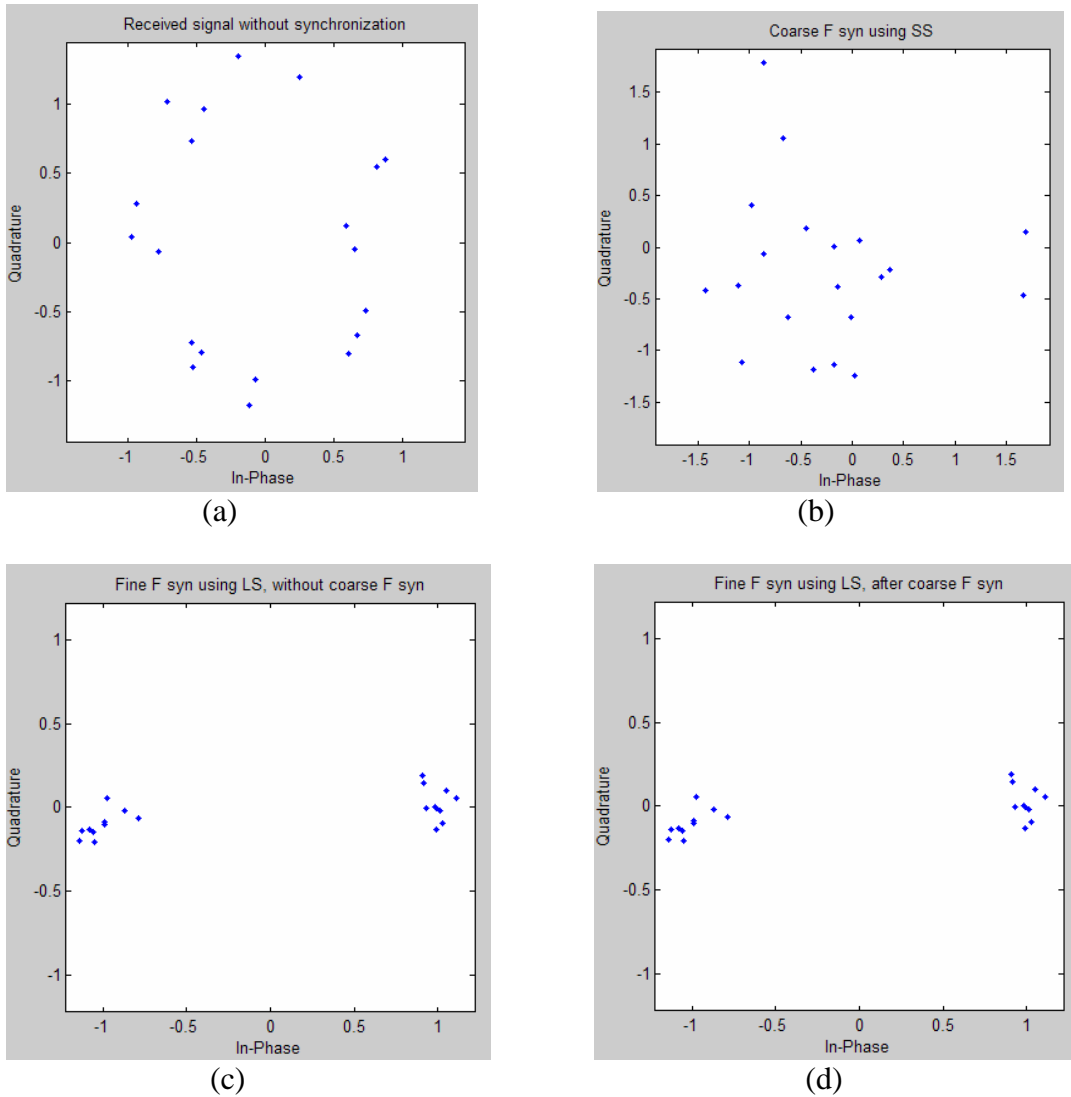

(a)

(b)

(c)

(d)

Figure 36.   Frequency synchronization effect in Signal 1.

Due to the small frequency offset that affects the signal, the channel and phase correction have not much to do, although we notice a very small correction in rotation in Figure 37.

(a)   (b)
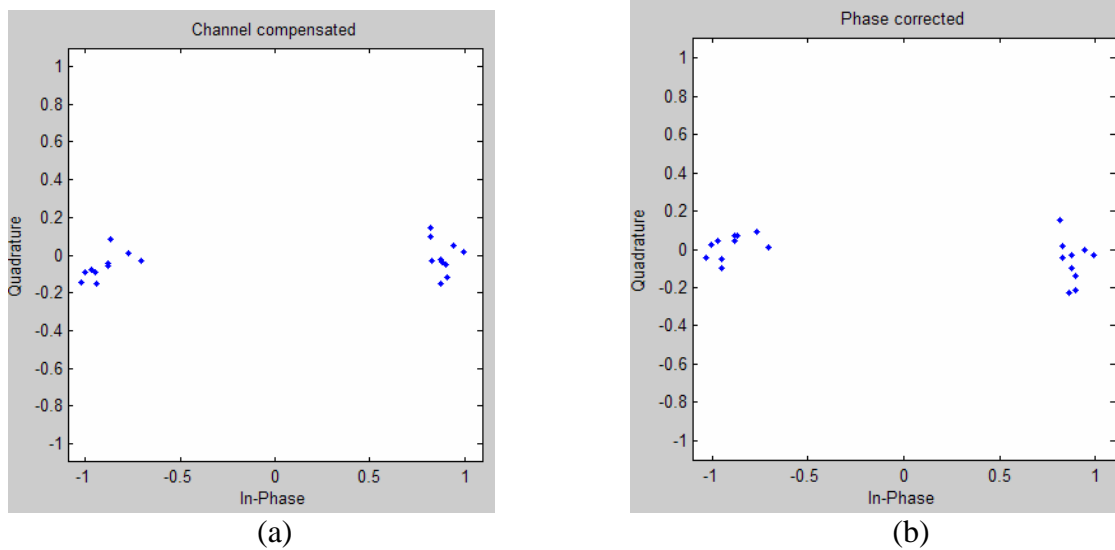
Figure 37.   Channel and phase correction of Signal 1.

2.   Signal 2

A frequency offset of 180 kHz has been added to Signal 2, in order to demonstrate the good result of having a coarse synchronization when a signal greater than 156 kHz in offset is processed.   Although letter (b) in Figure 38 seems to indicate that a coarse frequency correction does not help as expected, its effect is noted in letter (d), where the correction achieved by (b) is enhanced giving the depicted constellation. Letter (c) shows that a frequency correction using only the Long Preamble without a previous coarse correction, gives an incorrect result.

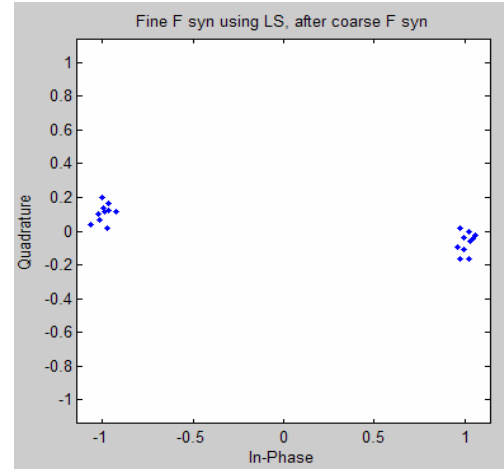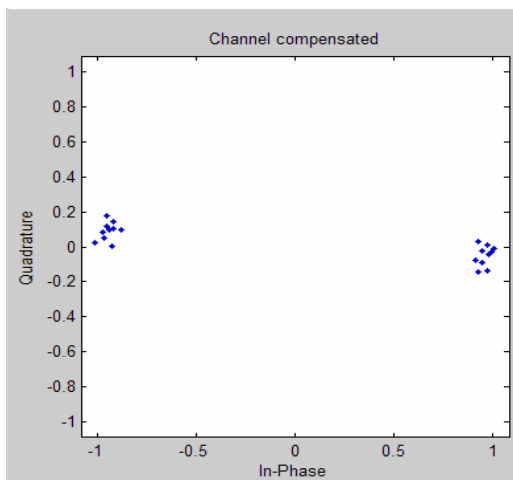In Figure 39 the results after channel and phase correction are shown.
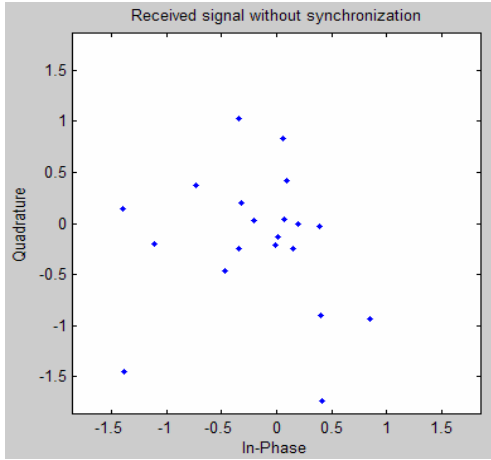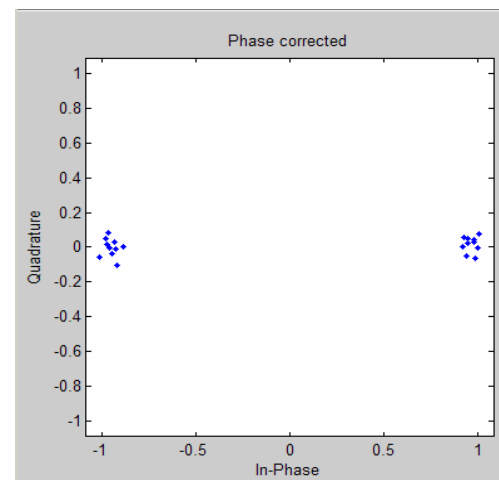
(a)
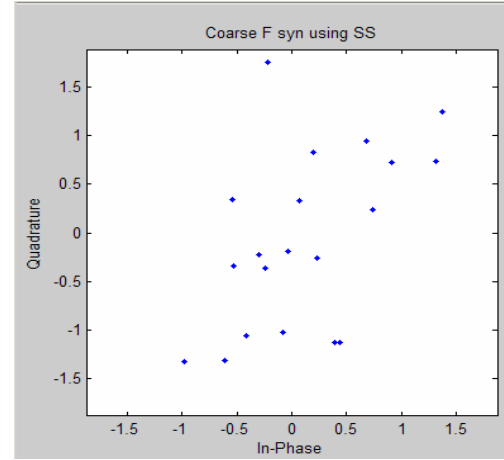
(b)
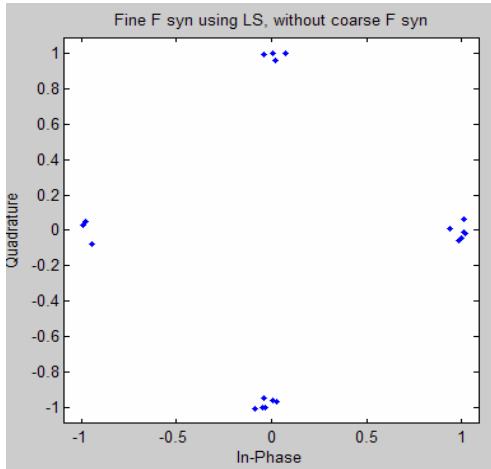
(c)

(d)

Figure 38.   Frequency synchronization effect in Signal 2.

(a)

(b)

Figure 39.   Channel and phase correction of Signal 2.

3. Signal 3

The goal in this signal is the same as in Signal 2, but transmitting a packet modulated in QPSK, where the frequency offset has a major impact in the signal. Figure 40(c) and (d) show the same effect as with signal 2, where two steps of frequency correction obtain better results.
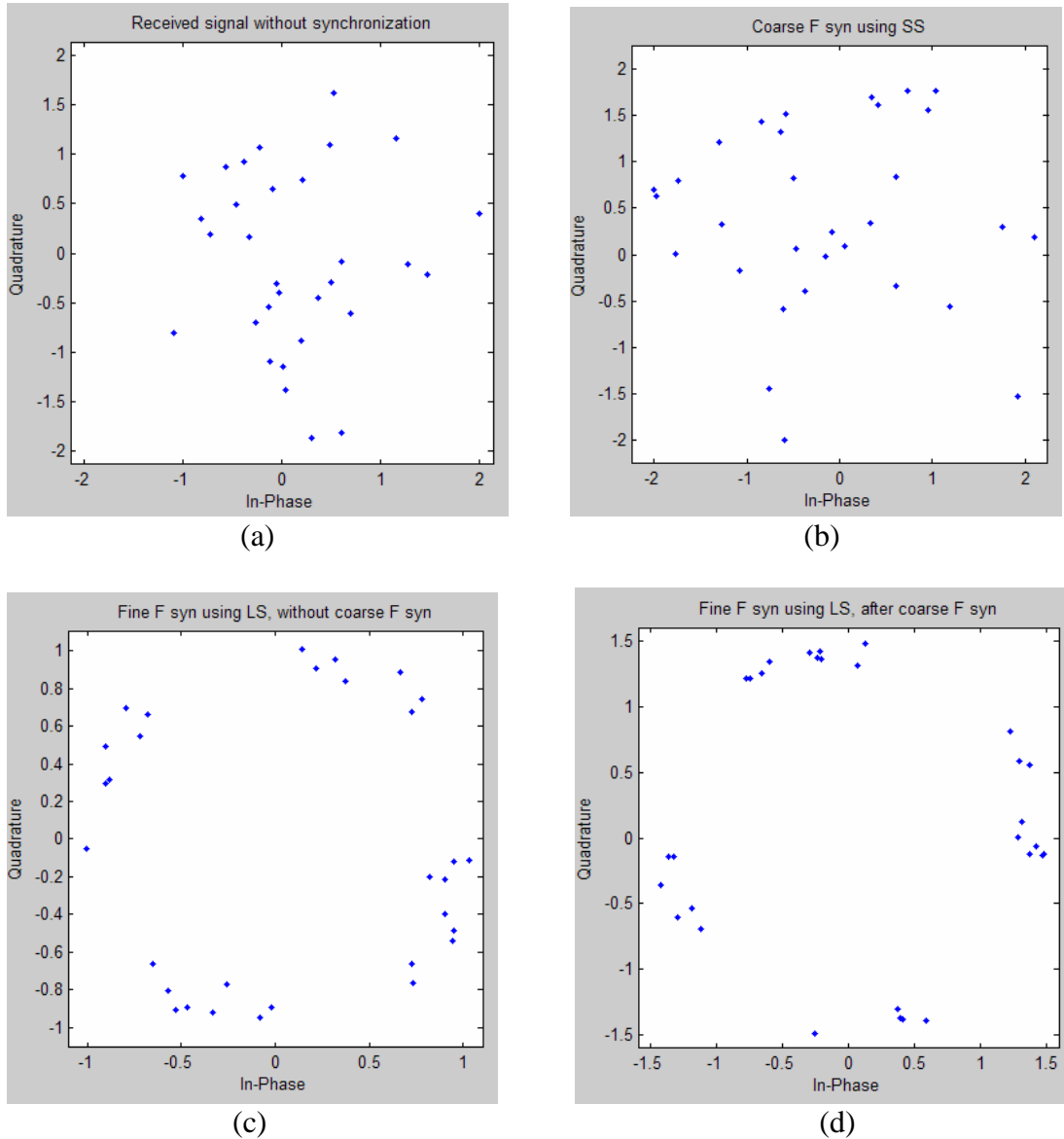

(a)

(b)

(c)

(d)

Figure 40.   Frequency synchronization effect in Signal 3.

In the case of this QPSK signal, as depicted in Figure 41, a last correction in phase noticeably improves the constellation, and therefore the receiver performance.
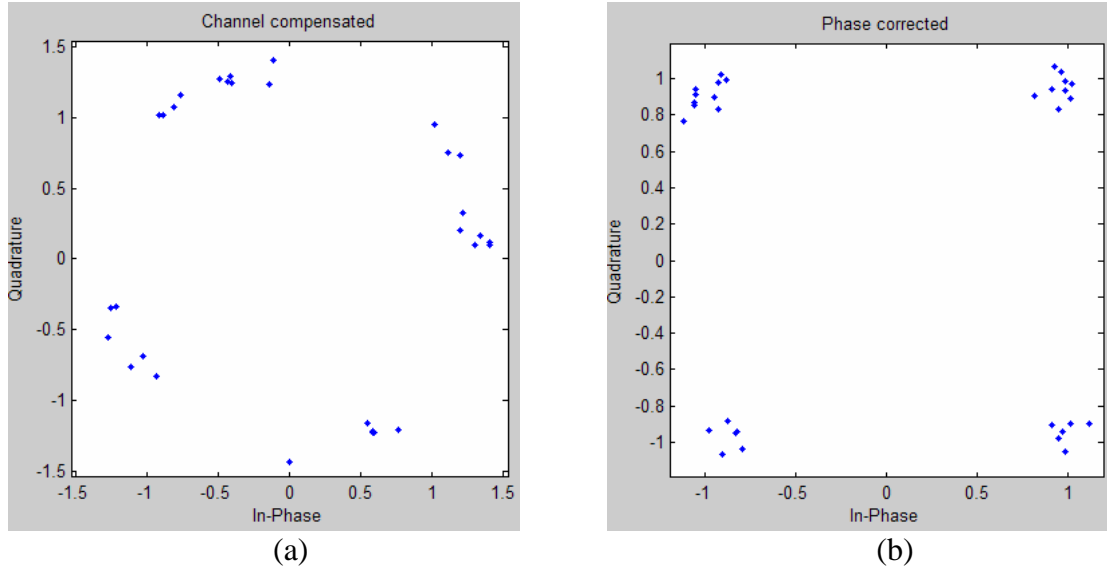

(a)   (b)

Figure 41.   Channel and phase correction of Signal 3.
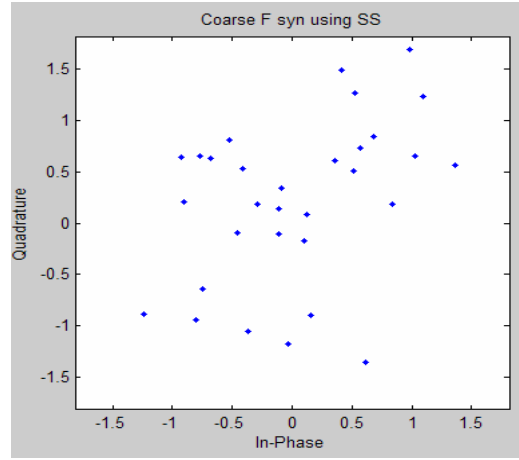
4.   Signal 4

This signal is put under 20 kHz of frequency offset and includes a second path delayed 0.6 μs, which is less than the CP, hence does not affect the packet after synchonization. Figure 42, again shows that a small frequency offset does not need two steps of frequency synchronization.

The same Matlab program used for generating the desired signal is utilized to analyze the files created by the testing waveforms. At the same time, the digital samples obtained after the last step of the synchronization, which is the phase tracking, are compared to the original ones, in order to determine the amount of errors. The results after applying a second path of 0.6 μs gives zero errors.
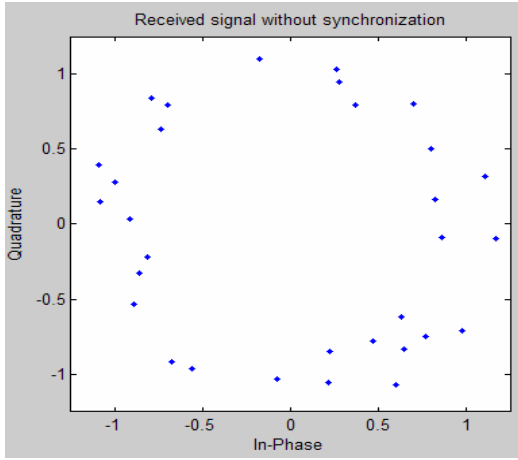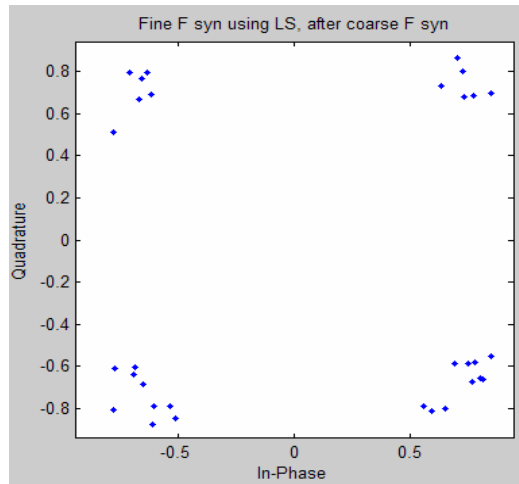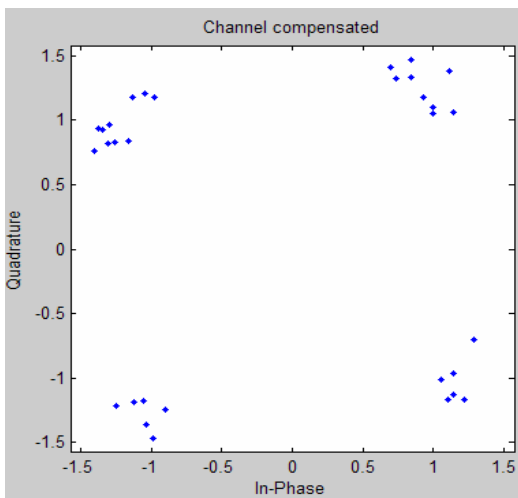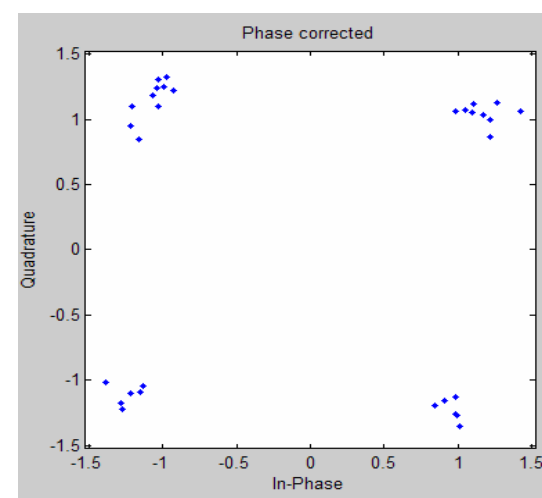
(a)

(b)
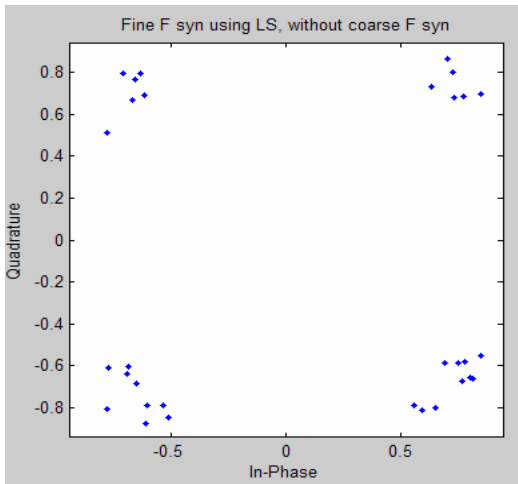
(c)

(d)

Figure 42.   Frequency synchronization effect in Signal 4.

(a)

(b)

Figure 43.   Channel and phase correction of Signal 4.

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5.   Signal 5

This signal keeps the 20 kHz frequency offset as with Signal 4, but now includes a second path delayed 1.2 μs, which is greater than the CP. As expected, the resulted digital samples give 20 errors after comparing to the original signal. Figure 45 shows in (d) a non perfect constellation, where the 20 errors are not appreciated because the graph is showing only one sub-carrier.
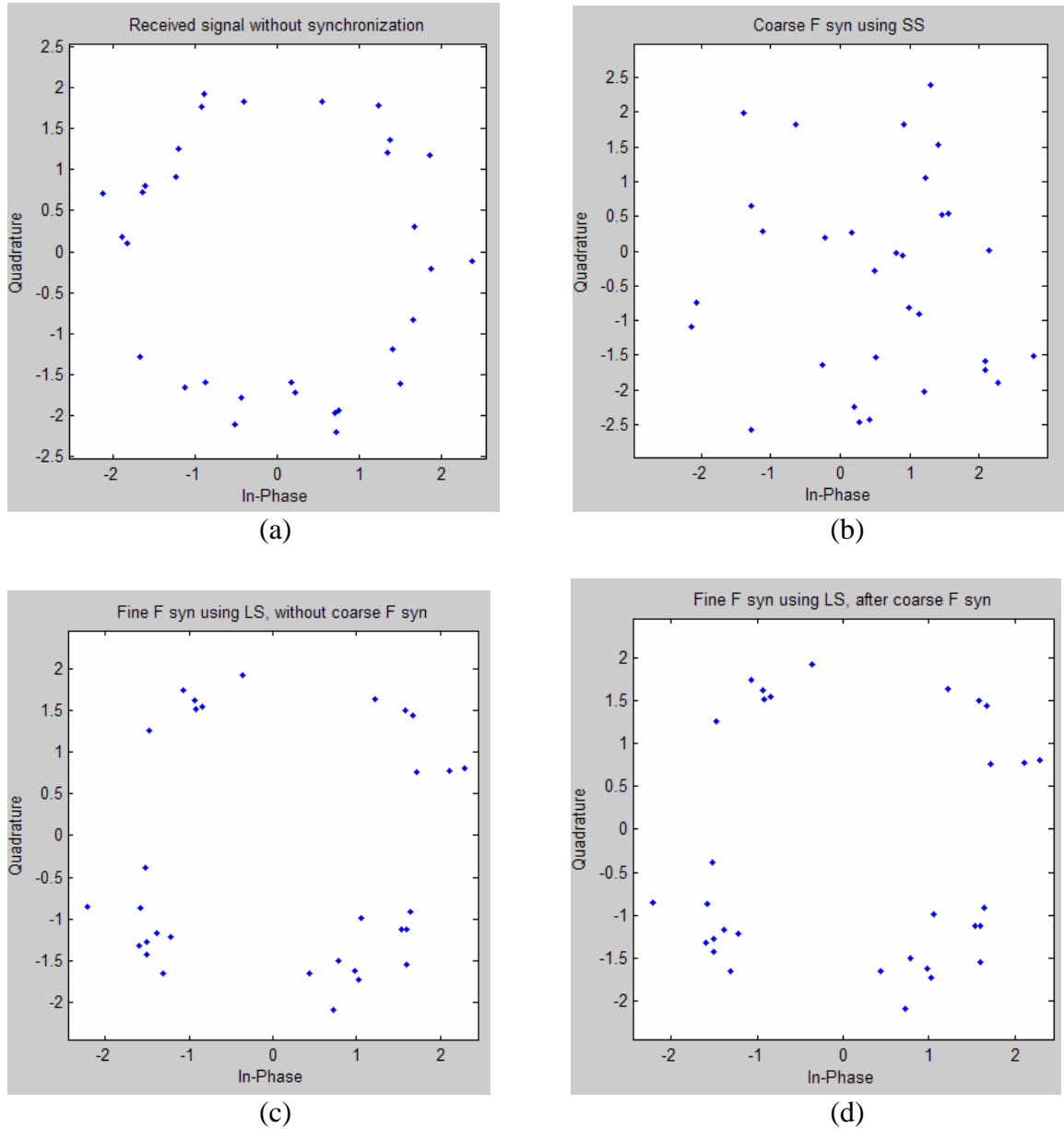

(a)

(b)

(c)

(d)

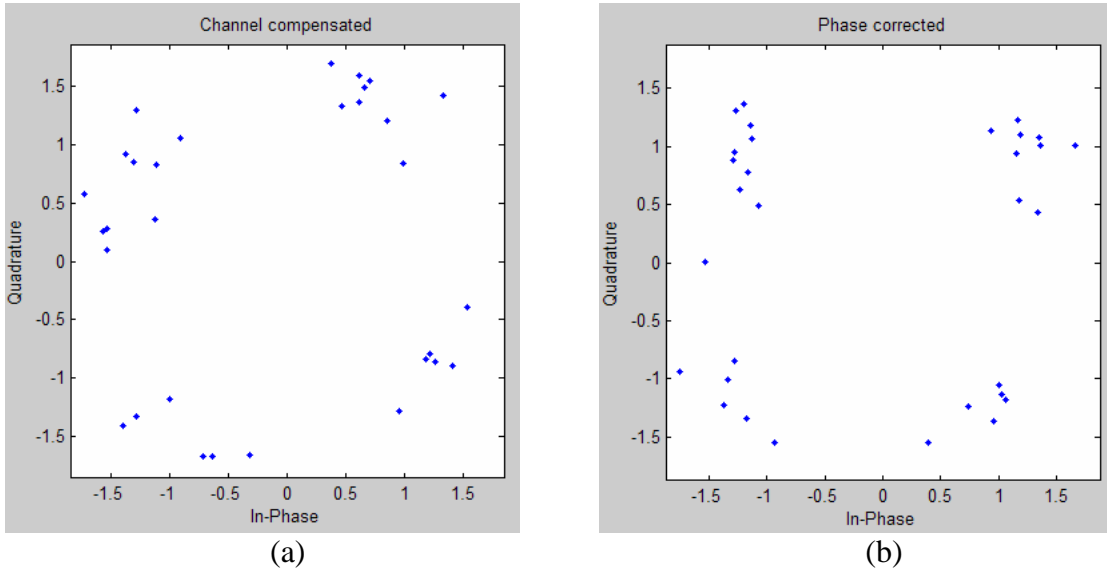Figure 44.   Frequency synchronization effect in Signal 5.

Figure 45.   Channel and phase correction of Signal 5.

6.   Signal 6

This last generated signal contains a frequency offset of 160 kHz, thus two steps of frequency synchronization are required. In addition to this, four paths are included, all of them delayed within the CP time. In order to realize the indispensable work of the synchronization chain in OFDM transmissions, six sub-carriers are shown in the graphs.

With six sub-carriers is difficult to appreciate the effect of frequency correction, as shown in Figure 46.

As depicted in Figure 47, after channel compensation the constellation becomes more clear. Then the last rotation enhancement is caused by the phase tracking step.

This last signal demonstrates that the synchronization process achieved by the algorithms discussed in this work enhance noticeably an OFDM signal affected by noise, frequency offset and multipath. A correct start packet sample identification will ensure avoiding ISI and ICI as explained in section II.B.2. If the start sample calculated is after the actual one, the symbols will contain information from the next symbol's CP. If the start sample is selected before the actual one, the multipath delay spread accepted will be shorter. The limit in the frequency offset is imposed by the coarse synchronization using

Short Sequence, which is 625 kHz, as indicated in section III.A.4.b, although the maximum allowed by 802.11a is 212 kHz. The main constraint is the multipath delay spread, which will cause errors if it is longer than the CP. This is unlikely for indoor operation.

(a)

(b)

(c)

(d)

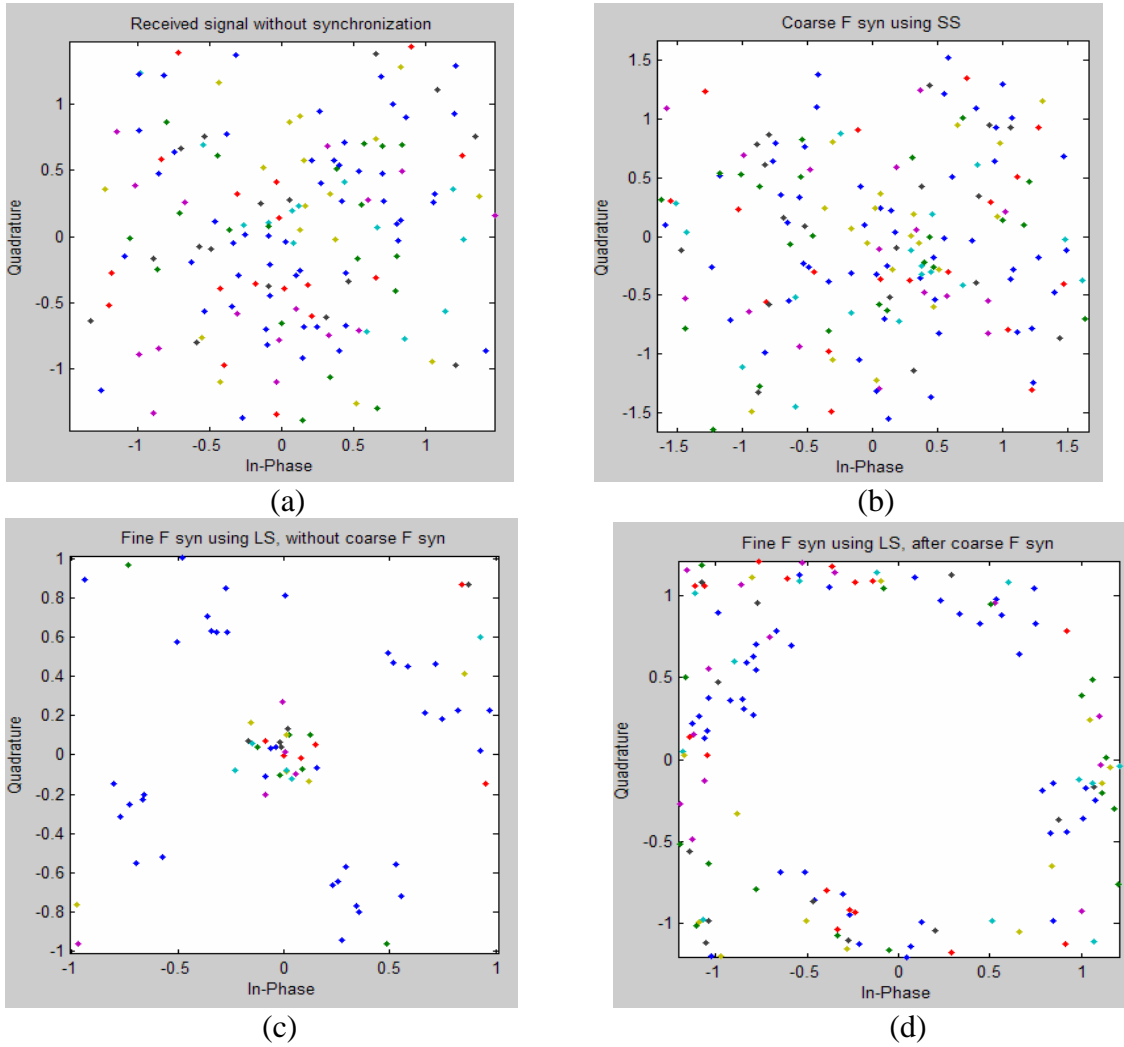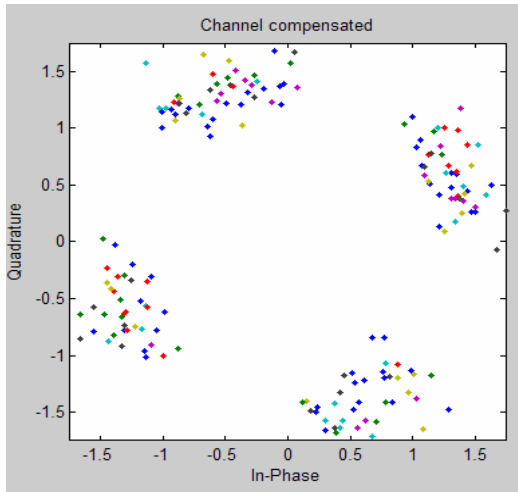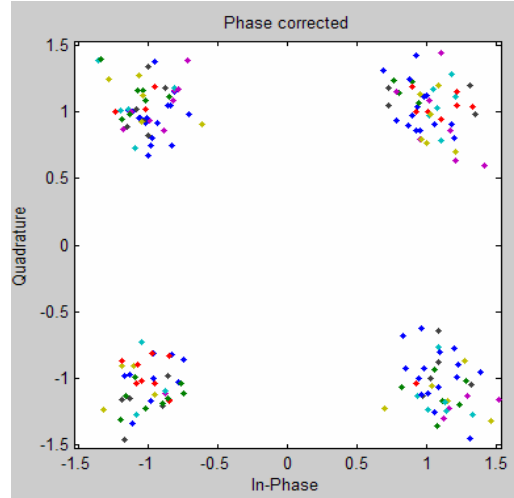Figure 46   Frequency synchronization effect in Signal 6.

(a)   (b)

Figure 47.   Channel and phase correction of Signal 6.

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VI. CONCLUSIONS AND FUTURE WORK

A. SUMMARY OF WORK

This thesis describes the design of a synchronization stage for an 802.11a software defined receiver. The software used to accomplish this goal was OSSIE, which includes a component and waveform development tool called the OWD. The application is based on the development of components for each specific synchronization type required in an OFDM signal transmission. One of the goals was developing these components using an open architecture to allow reuse for other OFDM standards.

The use of Matlab at the beginning of the work was essential for verifying the correct implementation of the algorithms obtained from the literature. After this process the next step was programming the components in OSSIE and testing them against the results obtained in Matlab.

Due to the throughput that 802.11a signals process and the limitations of our hardware, the testing part of this work was based on simulated data generated by Matlab, which used the standard packet structure affected by noise, frequency offset and multipath. The results obtained showed the correct functionality of the components through a visual demonstration using constellation diagrams, and a data comparison against the generated signal, giving the error count after the synchronization stage performed by OSSIE.

B. SUGGESTED FUTURE WORK

In order to obtain a complete and efficient 802.11a waveform implemented in OSSIE, the following future work is recommended.

1. Demodulation and Codification Components Upgrade

The group of components developed by Leong [7], should be upgraded to the current version of OSSIE, which is 0.6.1, and integrated with the synchronization

components designed in this work. Additionally, the following modifications should be performed to fulfill the structure followed by the synchronization components:

a. *Initialization Circuit*

The decodification component in charge of extracting the information of *signal* frame should have a dedicated port to inform the *Initialization_Register* component when the current packet has ended. Another way to accomplish this is to pass the *Initialization_Register* the length of the packet and make the necessary modifications to calculate when the packet will end.

b. *Connection Between Synchronization and Decoding Components*

When creating the 802.11a waveform, the last component of the synchronization stage that should be considered is *Phase_Trk.* The first component in the decodification stage should be the one in charge of the *signal* frame recovery.

2. Real Data Test

After having all the components working properly, the next step is to test the 802.11a waveform with real data from the air. The aforementioned USRP board is limited to the data rate accepted by the USB port, which is not enough to manage an 802.11a waveform. A recently announcement from Ettus, the USRP manufacturer, indicates that a new USRP is under development, which will include an Ethernet port that will permit a much greater transfer rate. With this new board, the USRP2, it will be possible to send an 802.11a sampled signal to the PC and process the data in the corresponding waveform. A USRP control component should be developed in order to read the digitized signal and send the samples to the first component in the synchronization stage, which is *Delay_Corr.*

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